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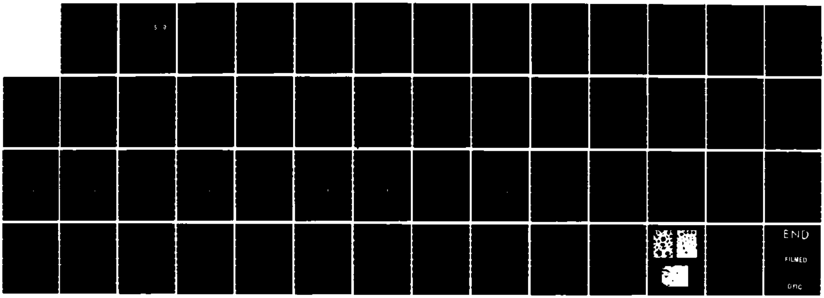

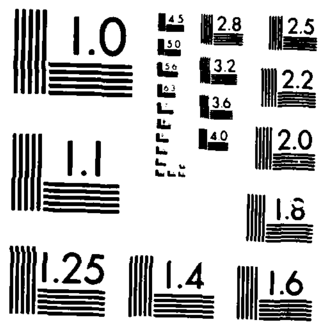

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HEARING PROTECTION AGAINST LOW FREQUENCY WEAPON NOISE

FINAL REPORT

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CURTIS R. SMITH

~~February 20, 1986~~
December 5, 1983

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The purpose of this investigation was to determine the material properties that are responsible for low frequency (100 Hz) noise attenuation in foam earplugs. An attempt was made to determine the following for each earplug type investigated: (1) chemical structure; (2) energy absorption at low frequencies, (3) noise attenuation as a function of foam density; and (4) the foam geometry. One experimental foam ~~had been~~ (was) found to give good low frequency noise protection but the physical properties responsible are unknown.

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Earplug materials tested were either polyvinyl chloride or polyurethane. All the commerical plugs contained some extractable plasticizer. Energy absorption was measured on two different dynamic mechanical analysis testers. Density was determined from weight and volume measurements and foam geometry was determined microscopically. Although the properties of foam varied ~~over~~ a wide range, no property was found which gave a reasonable correlation with the foam's ability to attenuate low frequency noise. A suggestion is made for the collection of air permeability data, along with the basis for that suggestion. One additional foam material was found which gave reasonable low-frequency noise attenuation in tests on the laboratory manekin. Some real-ear testing has been conducted by U.S. Army personnel.

Summary:

Hearing impairment is the most prevalent employment related disability in the country. Besides the emotional discomfort and reduced occupational performance suffered by hearing impaired persons, compensation for hearing loss costs employers hundreds of millions of dollars annually. Payments to veterans for hearing impairment suffered in the military service exceeds 54 million dollars annually. Thus both humane and financial considerations require effective hearing protective devices.

Hearing loss is most often the result of exposure to excessive noise. Elimination or reduction of noise is the ideal way of preventing hearing loss, but is not practical in many military situations. Although hearing protective devices are issued to military personnel, there are particular noise sources against which these devices are not very effective. The foam earplugs approved by the Army provide minimal protection against noise in the 100 Hz range. This study was carried out to try to find out what physical properties of foam earplugs were responsible for the noise attenuation at various frequencies. The anticipated result of the work was the ability to design a better hearing protective device.

A variety of physical measurements and chemical analyses were performed. Earplug weight, volume, density, foam cell size and dynamic energy absorption were measured. Earplug materials tested were either polyvinyl chloride or polyurethane. All commercial foam plugs contained some extractable plasticizer. Energy absorption was measured as a function of frequency on two different dynamic mechanical analysis testers. Density was determined from weight and volume measurements on individual earplugs, and foam geometry was determined microscopically. No consistent relationship was found between noise attenuation and any material property.

Two earplugs having a rather fine grained surface gave the best attenuation. This observation coupled with the known importance of fit in premolded solid earplugs led to speculation that air permeability might be a critical factor. At the completion of this contract, air permeability studies had not begun. At the time of submission of this corrected final report; however, the speculation has been tested and verified. Based on tests with the Knowles Electronic Manikin for Acoustic Research there is a positive correlation between air permeability of an earplug and the amount of low frequency noise which passes from the environment into the ear. The work on air permeability is continuing and real ear testing continues to be performed by U.S. Army personnel.

Foreword:

The authors believe that the information presented herein is accurate and that the opinions expressed are justified; however, neither the authors Auburn University or the Department of the Army assume any obligation or liability for the use of these results. Citations of commercial organizations and trade names in this report do not constitute an official Department of the Army (or Auburn University) endorsement or approval of the products or services of these organizations.

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HEARING PROTECTION AGAINST LOW-FREQUENCY, WEAPON NOISE

Introduction

Hearing loss is most often the result of exposure to excessive noise. Although hearing protective devices are issued to Military personnel, there are particular noise sources against which those protective devices are ineffective. In particular, the foam earplug approved by the Army provides minimal protection against the noise generated by some new weapons systems (centered about 100Hz). Elimination of noise through engineering controls is possible in many industrial settings but is not easily achieved in Military operations. The noise encountered when firing weapons and working around aircraft is unlikely to be reduced to an unharmful level; therefore, effective hearing protective devices are and will continue to be necessary.

Hearing impairment is the most prevalent employment related disability in the country. Besides the emotional discomfort and reduced occupational performance suffered by hearing impaired persons, compensation for hearing loss costs employers hundreds of millions of dollars annually. Payments to veterans for hearing impairment suffered in the military service exceeds 54 million dollars annually. Thus both humane and financial considerations require effective hearing protective devices.

Background

As indicated, hearing protective devices are necessary in a variety of military environments. Premolded solid polymer earplugs have almost universal use, but a number of researchers have questioned their effectiveness (1-4). Some investigators (5-7) suggest that inadequate fit of these devices is the primary reason for their lack of effectiveness. Limited earplug sizes (small, medium, and large) and uncertainties in measuring with ear calibrators make proper fitting of premolded solid polymer earplugs unlikely.

Flexible foam earplugs appear to be a practical alternative to premolded solid polymer plugs for two reasons: 1. foam earplugs can be compressed, inserted into the ear canal, and then allowed to expand to seal the canal, and 2. Ear canal measurements are not necessary in order to use these plugs. Flexible polymer foam has been developed for earplugs by commercial companies and approved by the Army as hearing protective materials.

A Government publication (8) has ranked hearing protective devices in order of effectiveness indicating that differences exist between various earplugs, including those constructed of foam. Other data (9) show that protective effectiveness is less, at low frequencies, and that differences between plugs are accentuated at low frequencies. At least one study has tried to determine what properties of a foam earplug make it good or poor as a hearing protector (9). In that study all the earplugs gave reasonably good attenuation at high frequencies (800 Hz).

The physical properties of plugs, at least in the range of properties available, had only a small effect on attenuation. There were some small, but statistically significant differences between plugs at high frequencies. At low frequencies there were large differences between plugs. A large amount of this variation was attributed statistically to the unquantifyable variable, composition. This really means that there are differences between earplug types, which are not explained by the physical properties. Physical properties, however, were unavoidably confounded with the composition variable i.e. the heaviest, and most dense plugs all were from one composition. In short, we do not have a good understanding of what material properties affect attenuation.

The purpose of this research was to develop an understanding of the relationship between material properties and noise attenuation of foam earplugs. The research concentrates on low-frequency noise because:

1. It is of interest to the Army.

2. Commercial foam earplugs are less effective at lower frequencies than at higher frequencies. One experimental earplug produced significantly higher attenuation at frequencies below 125 Hz, however, it was unsuitable because of a water soluble plasticizer and the company which produced it has ceased to exist.

3. Commercial instrumentation is available for measuring potentially important material properties at low frequency.

4. There are significant differences in attenuation among various types of earplugs at low frequencies, which leads one to expect that improvements are possible.

The Approach to the Problem

Specific experiments were run to determine:

1. Chemical composition of available foam earplugs.

2. Energy absorption capacity at low frequency (to see if ability to absorb energy is related to attenuation).

3. Noise attenuation as a function of a foam density over a wide density range.

4. Foam geometry, i.e., the size and wall thickness of the cells in the foam.

Experimental

Attenuation Measurements

The test environment was an Industrial Acoustics Company (IAC 1200 series) double wall room which had been modified to conform to the requirements of the American National Standards Institute (ANSI) standard method for the measurement of "Real-Ear Protection of Hearing Protectors and Physical Attenuation of Earmuffs" (ANSI S3. 19-1974). The instrumentation used to generate the sound field for

this investigation included a Bruel and Kjaer (B & K) type 1405 noise generator, a McIntoch type 2505 power amplifier, and an Altec speaker system type 604-8G. The sound pressure level (SPL) in the room was adjusted to 100dB. All noise attenuation measurements were made utilizing a Knowles Electronic Manikin for Accoustic Research (KEMAR). KEMAR was located in the center of the sound field. The SPL of the noise in KEMAR's ear canal was transduced by a B & K type 4134 one-half inch condenser microphone, fed to a B & K type 2619 microphone preamplifier, then on to B & K type 2606 microphone amplifier, through a Gen Rad type 1932D Fast Fourier Transform (FFT). The FFT was utilized as a computer system to manipulate, store, and output the collected data. The method of determining the attenuation of the earplug under test was to compute the difference in the SPL measured in KEMAR's ear canal with and without the properly inserted earplug. Each earplug was compressed by twirling lengthwise between the thumb and forefinger. The earplug was then inserted and released in KEMAR's ear canal, and was allowed to expand two minutes prior to attenuation measurements.

A variety of foam materials were tried including all the available foam earplug materials and a number of foams designed for gaskets and other applications. If the foam material was not available in earplug form, it was cut to a cylindrical shape using a cork borer.

Chemical Analysis

A chemical analysis was attempted on the commercial foam earplugs. Many if not most polymeric foam products have a placticizer added to increase the flexibility of the composition, to improve mechanical processing, or simply as an extender to reduce cost. Plasticizers are most often lower in molecular weight than the base polymer and can frequently be extracted from the polymer by solvents. A good extraction solvent is one in which the plasticizer is soluble but in which the polymer is insoluble. Since the plasticizers were unknown materials, solvents were selected with a range of polarity to try to ensure plasticizer solubility. The solvents selected were methanol, acetone and heptane. Plugs based on PVC (polyvinyl chloride) were partially soluble in warm acetone, so this solvent was not used with PVC plugs. The samples were extracted in a soxlet apparatus and after several trials the procedure described below was adopted (the procedure for PVC samples omitted steps 6 and 7):

1. Samples were sliced into wafers not exceeding 1/16 inch thickness.

2. Samples were weighed at ambient conditions.

3. Extraction thimbles (with a small hole in the bottom to allow drainage) were in use.

4. Samples were extracted in methanol for at least six hours (>10 cycles).

5. The methanol (containing any extracted material) was evaporated almost to dryness and then stored for further analysis.

6. Samples were extracted with acetone for at least six hours (>10 cycles).

7. The acetone (containing any extracted material) was evaporated almost to dryness and then stored for further analysis.

8. Samples were extracted with hexane for at least six hours (>10 cycles).

9. The hexane (containing any extracted material) was evaporated almost to dryness and stored for further analysis.

10. Extracted foam was oven dried at 60°C, then conditioned (at ambient) and weighed to determine the amount of plasticizer removed.

The infra-red (IR) spectrum of extracted plasticizer in each solvent was run on KBr window in a Perkin Elmer 735 infrared Spectrophotometer. The solution was coated on the window and the solvent allowed to evaporate before the spectrum was determined. Windows were cleaned and checked for infrared absorption before each sample was run. The infrared spectrum of the extracted foam plugs were run in KBr mull. Each plug was ground in water suspension in a blender and (after drying) was mixed with KBr in a vibratory mill.

Chemical microanalysis was done for carbon, hydrogen nitrogen and chlorine on the extracted foam. The material unaccounted for in these determinations is presumed to be oxygen. Single determinations were done, but since several extraction procedures were tried with similar results in microanalysis, the single point measurements are adequate.

Energy Absorption

Intuitively, the property in this study which was considered most likely to give a correlation with attenuation was energy absorption or dissipation. This property is measured by the quantity tan δ , where δ = the phase angle between applied cyclic deformation and the resulting cyclic stress. The quantity tan δ is a measure of the portion of applied energy which is absorbed and dissipated through viscous processes (internal friction). If cyclic strain and stress are in phase ($\delta = 0$) then the test material is completely elastic and no energy is lost to viscous forces. If viscous processes are present the stress lags behind the strain by an angle. The tan δ resolves the stress into a viscous and an elastic component and represents the ratio between the components. Tan δ also represents the ratio between the loss modulus and the elastic modulus. The vector sum of the two components is the conventional Young's modulus.

The test instrument is not always capable of measuring at the desired frequency. In those cases one can make use of the time temperature superposition principle to extrapolate data beyond the frequency actually tested. The principle of time temperature superposition says that increasing the temperature of a viscous process has the same effect as increasing the time allowed for the process. In these cyclic tests, a lower temperature is equivalent to a higher frequency. Further, by making measurements over a frequency range at various temperatures, the frequency shift equivalent to a temperature change can be determined. The technique is shown in the Appendix B and it was used when necessary to obtain data at 100 Hz.

Some of the available plugs were tested for energy absorption. These were selected on the basis of their attenuation performance (the best and the worst for attenuation). Samples were tested on a Rheometrics Mechanical Spectrometer® at several temperatures and on an I-Mass Dynastat® at frequencies up to 100 Hz.

The Rheometrics Mechanical Spectrometer was used in a torsion mode and samples. were glued to the test jaws to prevent slippage between the jaws and sample.

The I-Mass instrument was used in a compression mode and due to the slow recovery of some of the materials, the samples were glued to the jaws so that contact with the jaws was not lost. For both instruments, the measured sample geometry and instrumental signals are input to a computer for the calculation of mechanical properties.

Several material properties can be measured with each instrument. Tan δ, the ratio between the energy dissipated through viscous processes and the recoverable elastic energy stored in the system, is of most interest.

Density of Foam

Density is the ratio of weight to volume. The volume of a sample was determined by measuring the dimensions of a piece of foam using verniner calipers and then weighing the foam on an analytical balance.

Foam Geometry

The foam cell size and wall thickness were determined microscopically. Sections were cut, both longitudinal and cross-section, by hand with a razor blade. Samples were photographed on the microscope stage along with a stage micrometer for size reference. The field of view in the photomicrographs was about 6 mm^2. Cell diameters and wall thicknesses were measured with a ruler on the photomicrographs. At least 25 measurements were taken unless the photomicrograph had less than 25 cells.

Earplugs Tested

The foam materials included most of the commercially available foam earplugs as well as a number of foams not designed as earplug materials. Not every foam sample was used for every test since some materials were characterized by the vendor and others were received and added to the program after some tests were completed. The following is a list of foam materials evaluated in some part of the project:

1. Ear: Commercially available from EAR Corporation - Indianapolis, Indiana.

2. Decidamp: Supplied by Marion Health and Safety - Rockford, Illinois - Reported to be the same as EAR except for color.

3. Norton Disposable Earplugs: Supplied by Norton Safety Products Company - Cranston, Rhode Island - No longer commercially availble.

4. Experimental earplugs supplied by Marion Health and safety under the Decidamp name (never sold commercially).

5. Hushler: Supplied by Protector Safety Products - London England.

6. Purafoam: Supplied by Mouldex Metric Inc. - Culver City, California.

7. Sound Less: Supplied by Willson Safety Products, Reading Pennsylvania.

8. Earplug foam sheet: Supplied by Specialty Composites, Inc. (reported to be similar to 7).

9. Cylindrical gasket foam (K2A00): Supplied by Norton Company Granitville, New York.

10. Weatherstripping (V5616, V5412, 101FA, and V4112) Supplied by Norton Company, Granitville, New York.

In order to simplify references to the particular earplugs throughout this report, the earplugs are coded as indicated in Table I.

TABLE I EARPLUG CODING

Earplug	Code	Earplug	Code
EAR	A	Specialty Composites Foam Sheet	H
Decidamp	B	Norton K2A00	I
Norton Disposable Earplugs	C	Norton V5616	J
Experimental Plugs from Decidamp	D	Norton V5412	K
Hushler	E	Norton 1015A	L
Purafoam	F	Norton V4112	M
Sound Less	G		

RESULTS

Results of attenuation measurements on commercial earplugs have been previously published (9, 10,) by the authors of this report. The previous results are shown in Figure 1. The results for noise attenuation at low frequency are broken out in Table II and results from other test material have been added. Results at 4000Hz. are also shown. All measurements presented here were made on KEMAR.

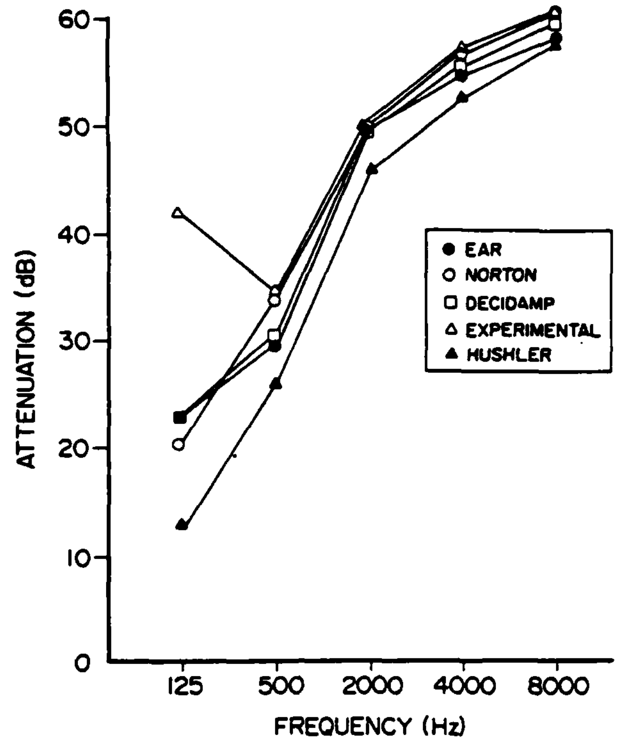

Figure 1. Noise Attenuation at Various Frequencies for Foam Plugs

TABLE II Noise Attenuation of Foam Materials

Earplug	125 Hz (dB)	Attenuation at 4000 Hz (dB)
A	23	55
B	22	56
C	20	57
D	42	57
E	13	53
F	22	50
G	11	53
I	37	62
J	22	53
K	6	39
L	24	52
M	6	27

Two of the foam materials (D and I) give good attenuation at low frequencies. The remainder are marginal to poor. All of the commercial foam earplugs give 50 dB of greater attenuation at 4000 Hz. In the previous work, the factors

which affected the attenuation were (in the order of importance) frequency, weight, composition, and density.

The effect of frequency was that all plugs gave good attenuation at high frequency and poorer attenuation at low frequency. Frequency is a test condition, however, rather than a plug attribute or material property. The most important material property was the unquantified attribute, composition. The variable, composition, is not easily quantified on a numerical scale but it contains a set of material properties not yet determined, or even completely indentified. The work proposed in this project could be viewed as an attempt to guess the important variables which make up the collective term, composition, and to measure the effect of these variables on attenuation at a particular frequency. Some of these variables such as density, weight, dimensions, moisture content, and expansion force (against the walls of a constructed ear canal) were measured in previous work (9, 10). These showed either a very small effect or an inconsistent effect which changed direction with the different brands, or at different frequencies. It is assumed that one or two material properties, not yet examined, would have good correlation with attenuation at low frequency. The properties selected for examination in this work were listed in the experimental section of this report and the results from these measurements follow.

Chemical Analysis

Chemical analysis was performed on commercially available earplugs. First, the plasticizer was extracted with solvents, and then chemical microanalyses were performed on the extracted plugs. The results of plasticizer extraction and chemical microanalysis are shown in Table III.

TABLE III Plasticizer Content and chemical analysis of Foam Earplugs

Earplug Type	Plasticizer Content (%)	Carbon (%)	Hydrogen (%)	Nitrogen (%)	Chlorine (%)	Difference Presumed Oxygen (%)
A	39.7	38.51	4.71	.56	47.93	8.29
B	42.4	38.4	4.71	.60	49.45	6.84
C	10.8	57.41	7.70	4.94	2.50	27.45
D	49.5	55.4	7.75	3.77	0.0	33.08
F	7.9	56.38	7.47	4.73	0.0	31.42

Infrared spectra were obtained for both the plasticizer and the extracted foam. Typical spectra appear Appendix A. Plugs A and B seem similar in elemental composition and in IR spectra. Both are high in chlorine content and are likely to be polyvinyl chloride with an ester plasticizer (phthalates are common).

With plasticized and filled polymer compositions, it is difficult to effect a complete separation of components. Both the earplug and the extracted plasticizer show a carbonyl absorption in the infrared, thus supporting the conclusion of incomplete plasticizer extraction. Both extraction solvents (methanol and hexane) seem to have extracted a similar plasticizer judged from its IR spectrum.

Plugs C, D, and F have substantial nitrogen in the chemical composition and carbonyl absorption in the infrared. This infrared suggests a polyurethane foam. The plasticizer content ranges from less than 10% to almost 50% and, in each case, has carbonyl absorption in the infrared. A comparison of all plasticizer, spectra shows similarities as well; not identical spectra, but indicating similar composition for all of the plasticizers. Not all of the foam materials were tested for chemical composition. In particular, the gasket and weather stripping materials were reported by the manufacturer to be plasticized, pigmented polyvinyl chloride. One other material supplied from Willson was reported by its manufacturer to be a polyurethane.

Recalling that the PVC gasket material gives good low frequency attenuation and that the PVC commercial plugs do not, and further that one polyurethane is much better than the other polyurethane, one cannot make a case that chemical composition is the important factor in low frequency performance of foam earplugs.

Energy Absorption

Energy absorption was measured in the Rheometrics Mechanical Spectrometer in a torsion mode. The tests were run at 35° , 20° , and 5° C, and samples were glued in the jaws to prevent slippage.

The measurements at 35° C were used as the base since it is about body temperature and the measurements at 20° and 5° C were used to extend the frequency (by time temperature superposition) to much higher values that allowed by the test instrument (see Appendix B). Three frequency values are reported in Table IV along with the tan δ measurement. The attenuation at 125 Hz is also included and shows no relationships with tan δ.

TABLE IV Energy Absorption of Foams During Cyclic Torsion

Sample	Tan δ at Various Frequencies 15.9 Hz	159 Hz	1590 Hz	Low Freq. Attenuation (dB)
D	.682	.374	.351	42
I	.437	.371	.356	37
A	.736	.795	.764	23
G	.913	.563	.391	11

Energy absorption was also measured using an I-Mass Dynastat Mechanical Analyzer at frequencies from 0.1 to 100 Hz. the results are shown in Table V. This test operated in the compression mode which intuitively seems a better model for sound waves than the torsion mode used in the Rheometric instrument. It was, again necessary to glue the samples in place to avoid separation from the jaws during the test. At some frequencies the force exceeded the range of the instrument drive/transducer system and peak displacement during the cycle could not be held constant. Such excursions were reported by the operator to be due to "resonance effects" in the sample. Samples which exhibit this problem were

cut in half and retested. In most cases the resonance disappeared, consistent with expected resonance behavior.

TABLE V Energy Absorption of foam During Cyclic Compression

Sample	Tan δ at Various Frequencies 25 Hz	40 Hz	63 Hz	100 Hz	Attenuation at 125 Hz (dB)
I	.43	.48	.55	.62	37
D	.59	.63	.65	.74	42
A	.63	.74	.75	1.0	23
C	1.22	1.21	1.24	1.24	20
G	.95	.96	.94	1.4*	11

* Abnormally high displacement - value in Table is likely to be in error

All samples gave reasonable values for Tan δ up to 25 Hz, beyond which some samples began to give variable displacement readings.

One might discern a trend in these data, that the best materials for attenuation (at 100 Hz) show the lowest Tan δ results. This is not what one would expect, however, if tan δ were controlling the noise attenuation since an increase in tan δ indicates an increase in the ability of a material to dissipate energy. We must conclude, then, that energy absorption is not the principal mechanism for noise attenuation.

Foam Geometry

Foam differs from other solids in that it consists of a dispersion of air pockets in solid material. It was considered likely that the arrangement of this dispersion, which might be characterized as foam geometry, might be important in determining attenuation. Certainly, if there are large interconnected air passages through the foam, attenuation will be reduced from that of a solid plug. Trials with KEMAR using a very low-density, open-constructed foam showed that attenuation was nil. The factors to be considered in the geometry of a foam material include the size and shape of the air pockets, the thickness of the walls between cells, whether the foam has open or closed cells, and the overall ratio of open space to solid volume.

Perhaps comment should be made about open vs. closed cells. When a foam is formed the cells tend to be spherical. Packed spheres do not completely fill space. In the case of spherical air pockets inside of a solid (or liquid since the foam is formed as a liquid) when the air pockets come together, the wall of solid material becomes thin or perhaps ruptured and non-existent (see Figure 2). Where the curvature of the air pockets leaves spaces between cells, the walls are thicker.

The mechanism for the collapse of a foam is that the material in the thin areas, where cells almost touch, drains to the thick areas, called Plateau borders, and eventually the thin wall ruptures. (Figure 2)

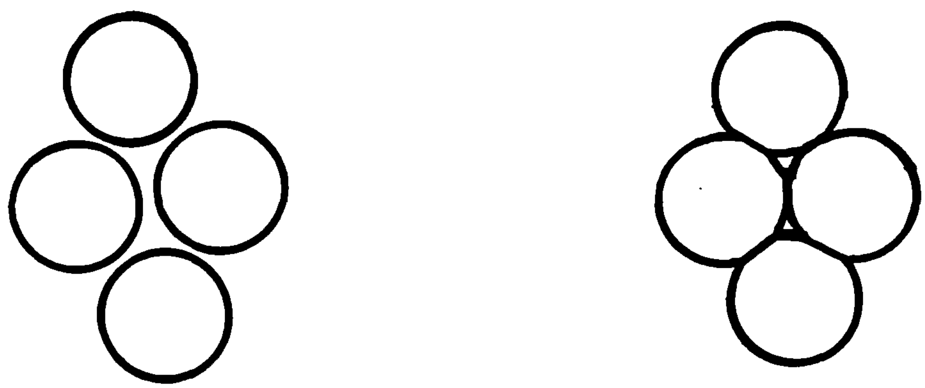

FIGURE 2. Collapse of Liquid Foams

Some treatments have been devised so that after the liquid foam has become solid, the thin cell wall regions can be selectively ruptured while leaving the thicker Plateau borders intact. While this post-treatment is not likely for ear plug materials, the natural process of cell wall thinning and rupture during manufacture certainly occurs.

For foams of similar chemical composition, density is a good measure of the void volume in the foam. Even with differences in chemical composition, if the foam is highly expanded, the density can provide reasonable estimate of void volume.

Foam geometry was examined microscopically and general comments concerning these observations appear in Table VI followed by specific measurements in Table VII. Representative photomicrographs appear in Appendix D.

The hole sizes were measured in two perpendicular directions on a photomicrograph. This was done so that if cells were elongated in one direction, the values obtained would represent a proper average dimension. Standard deviations of cell size were also calculated and, in general, bear out the visual observations concerning distribution of cell sizes. Recalling that samples D and I represent the best attenuation while G represents the worst at 100 Hz, there is no apparent correlation between cell dimensions and attenuation.

TABLE VI Visual Appearance of Micrographs

Sample	Comments
A	Large openings, some coalesced, relatively thick cell walls, cells rather spherical.
B	Similar to A.
C	Some large coalesced openings but many small ones thick cell walls (bimodal distribution) cells rather spherical.
D	Some large and medium sized cells but many small and very small cells, cells elongated in the cross section. Very thick walls in the longitudinal.
F	Large spherical cells or groups of smaller cells in the process of coalescing, some cells appear to be closed.
G	Some large and medium sized cells, but many very small cells as in D.
I	Large rather spherical cells in cross-section (some closed cells). Longitudinal section has thin walled polygons almost all enclosed (particularly the surface layer).

TABLE VII Measurements of Cell Size in Foam Earplugs

Earplug Type	Cell Size (mm)	σ	(mm)	σ	Average Cell Size (mm)	Cell Thickness Thickness (mm)	σ
A	0.192	0.097	0.219	0.178	0.206	0.059	0.0124
B	0.212	0.096	0.198	0.065	0.205	0.070	0.016
C	0.90	0.59	0.082	0.048	0.086	0.064	0.020
D	0.080	0.076	0.071	0.096	0.076	0.045	0.028
F	0.139	0.095	0.160	0.099	0.150	0.116	0.132
G	0.099	0.60	0.101	0.076	0.100	0.076	0.037
I	0.143	0.060	0.140	0.56	0.142	0.074	0.050

Density of each the plugs was determined and is shown in Table VIII. Density values are presented in ascending order and cover the range from 5 to 15 pounds per cubic foot. Once again there seems to be no relationship with noise attenuation.

TABLE VIII Effect of Foam Density on Noise Attenuation

Earplug	Density (g/cm^3)	Density (lb/ft^3)	Attenuation at 125 Hz (dB)
J	.0961	5.5	22
A	.099	5.7	23
B	.105	6.1	22
C	.110	6.3	20
G	.129	7.4	11
K	.136	7.8	6
I	.144	8.3	37
F	.148	8.5	22
M	.189	10.9	6
L	.251	14.4	24
D	.260	14.9	42

In summary, we have not found a consistent relationship between noise attenuation and any material property of foam earplugs. One other material was "discovered" which gave good noise attenuation in tests on KEMAR. This was sample I (Norton K2A00). This material is reported by the vendor to be a filled, plasticized PVC. It is extruded as a foamed one-half inch cylinder and therefore had an extremely smooth cylindrical surface. the production method offers obvious advantages in economy and simplicity of operation, but this particular composition has some problems. This composition appears to be somewhat damaged during compression and undergoes a permanent set or "breakdown" during extended compression. This particular composition is being tested on live subjects to see if the KEMAR data carry over into real-ear testing. Even then, some modification of the composition will be necessary to improve the resiliency.

In a visual comparison of structure with a magnifying lens one might make the case that the two earplugs having good attenuation have a fine grain or bubble size on the longitudinal surface. Perhaps the closeness of fit between the earplug and ear canal plays a roll with foam devices, even as has been proposed with solid polymer earplugs (5-7). It is reasonable that air permeability in a plugged artificial ear canal should reveal the closeness of fit. Although it was not proposed in this contract, a device for this measurement of air permeability through and around an inserted foam earplug is being constructed and will be used to gather this information.

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(Mr. Peter Herh, Mr. Fred Klein)

I Mass, Inc.: for rheometric testing
(Mr. E.J. Tolle)

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(Mr. Ben Mozo)

Albany International: for discussion concerning
sound transmission. (Dr. Robin Dent)

APPENDIX A

Infra-Red Spectra of Earplugs and Extract

NO. 007-1271

REMARKS Solid left after (2) extractions mulled c̄ K Br
Ear Plug Sample #21

ORIGIN

PURITY

SPEED NORMAL ✓ FAST

SLITS NORMAL ✓ WIDE

PHASE

CONCENTRATION

THICKNESS

DATE 6/14/83

OPERATOR

PERKIN-ELMER

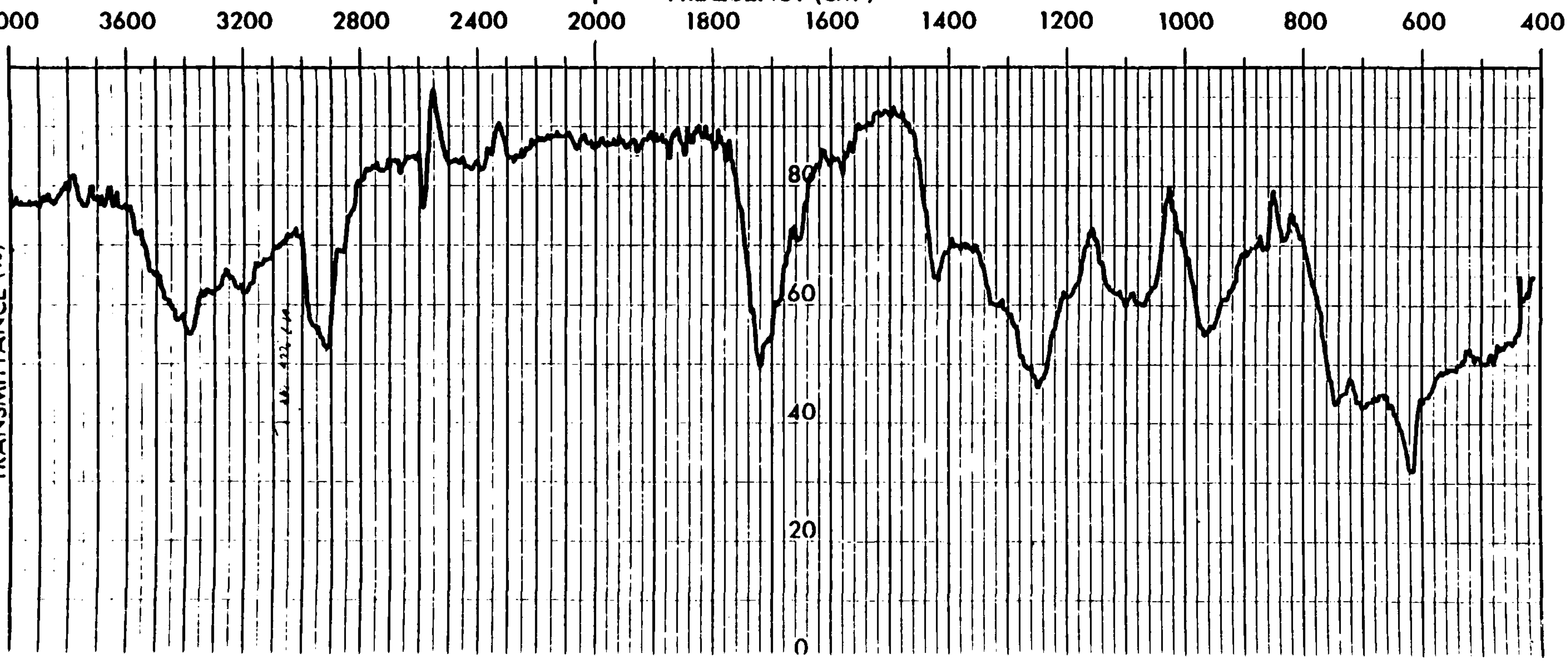
SPECTRUM NO.

SAMPLE 1 21
K Br Mull

SAMPLE 2

#

SAMPLE A - extracted foam SPECTRUM NO.



NO. 007-1271

REMARKS

Extraction from Ear Plug Sample #21 with Hexane

Transmittance Adjusted

ORIGIN

PURITY

SPEED NORMAL ✓ FAST

SLITS NORMAL ✓ WIDE

PHASE

CONCENTRATION

THICKNESS

DATE 6/14/83

OPERATOR

PERKIN-ELMER

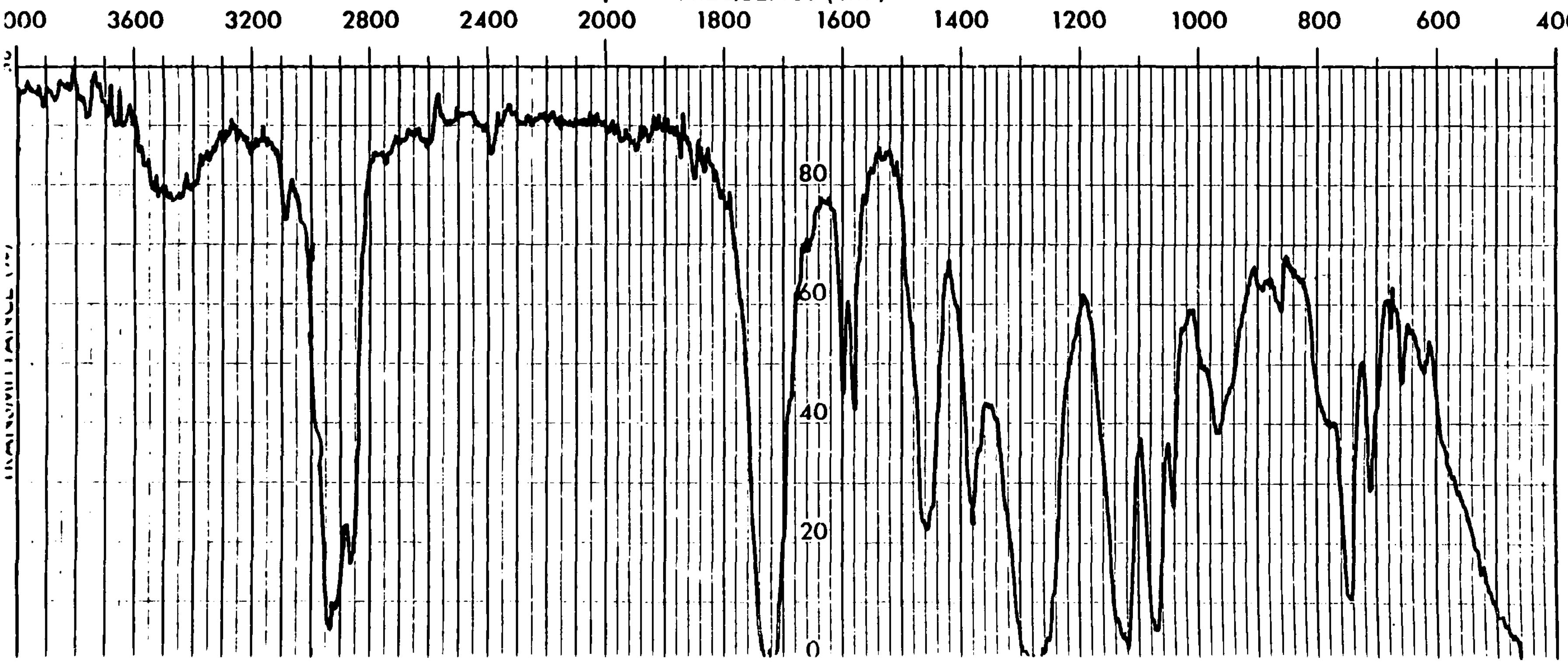
#1

SPECTRUM NO.

SAMPLE 1 21-H 21/H

KBr Window

SAMPLE 2



SAMPLE A - hexane extract SPECTRUM NO.

NO. 007-1271

REMARKS
Extract from Ear Plug
Sample # 21 with
Methanol
15 min. in oven @ 65° 70°C

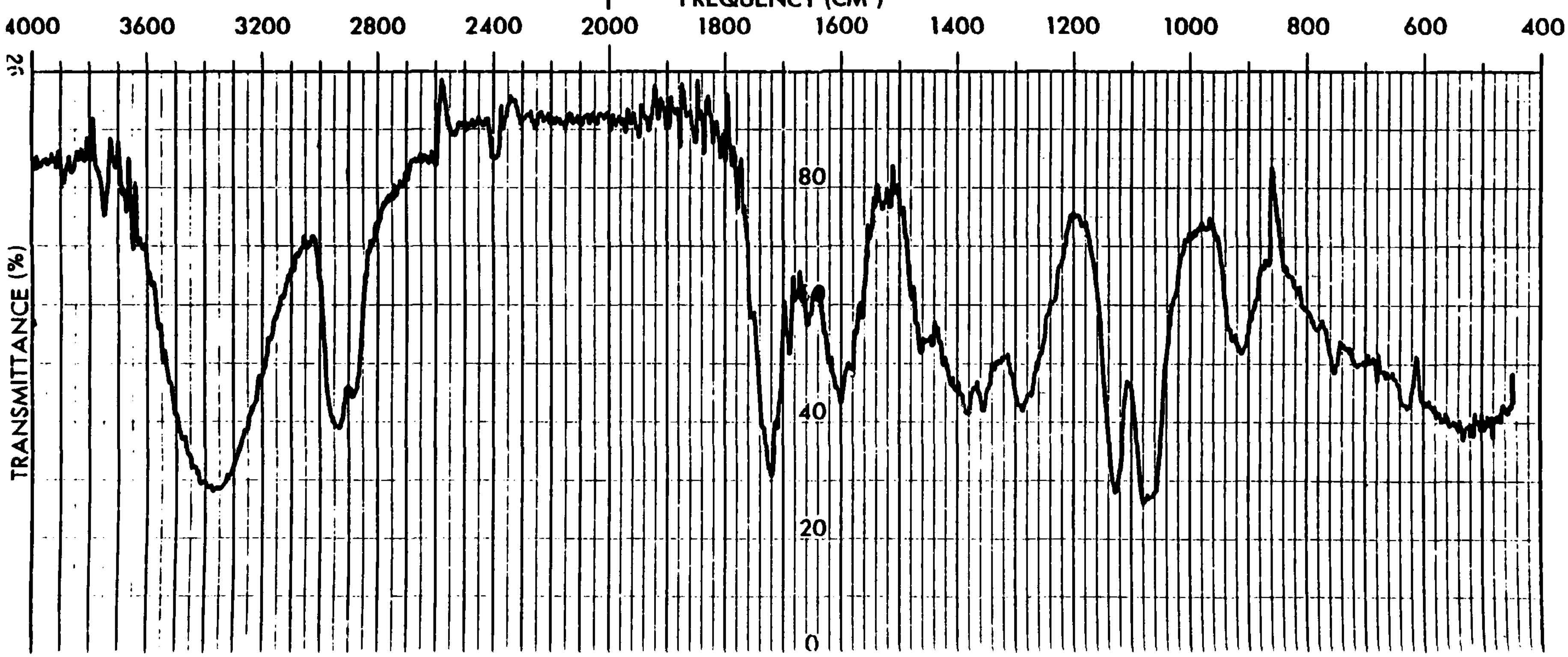
ORIGIN
PURITY

SPEED NORMAL ✓ FAST
SLITS NORMAL ✓ WIDE
PHASE
CONCENTRATION
THICKNESS
DATE 6/16/83
OPERATOR DD

PERKIN-ELMER

SPECTRUM NO.
SAMPLE 1 21 M
KBr Window

SAMPLE 2



SAMPLE A - methanol extract SPECTRUM NO.

NO. 007-1271

PERKIN-ELMER

REMARKS
Solid from (2) extractions of Ex Plug Sample #22

ORIGIN

PURITY

SPEED ____ NORMAL ✓ FAST

SLITS ____ NORMAL ✓ WIDE

PHASE

CONCENTRATION

THICKNESS

DATE 6/14/83

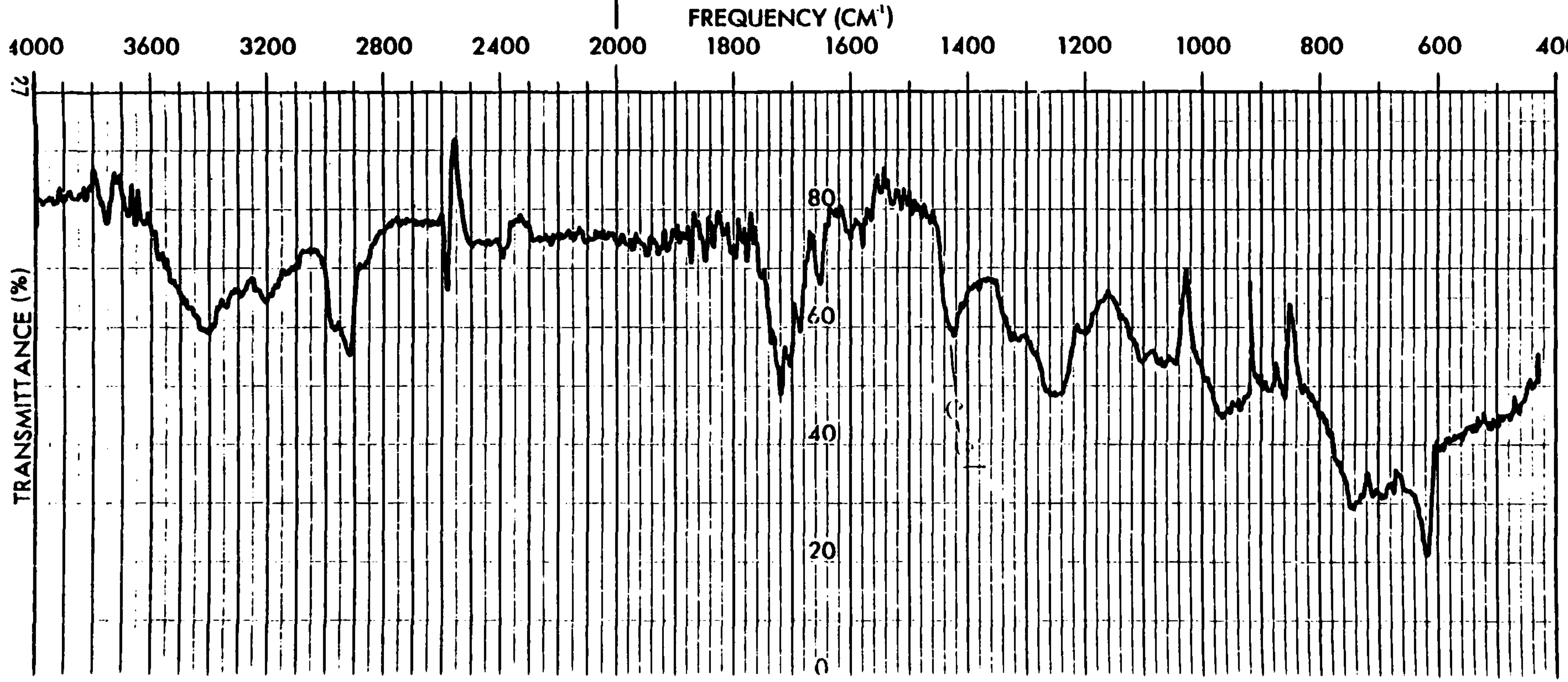
OPERATOR

SPECTRUM NO.

SAMPLE 1 22
K Br Mull

SAMPLE 2

SAMPLE B - extracted foam SPECTRUM NO.



NO. 007-1271

REMARKS
Extract from Ear Plug Sample
#22 with Hexane

Dried in Dessicator

ORIGIN
PURITY

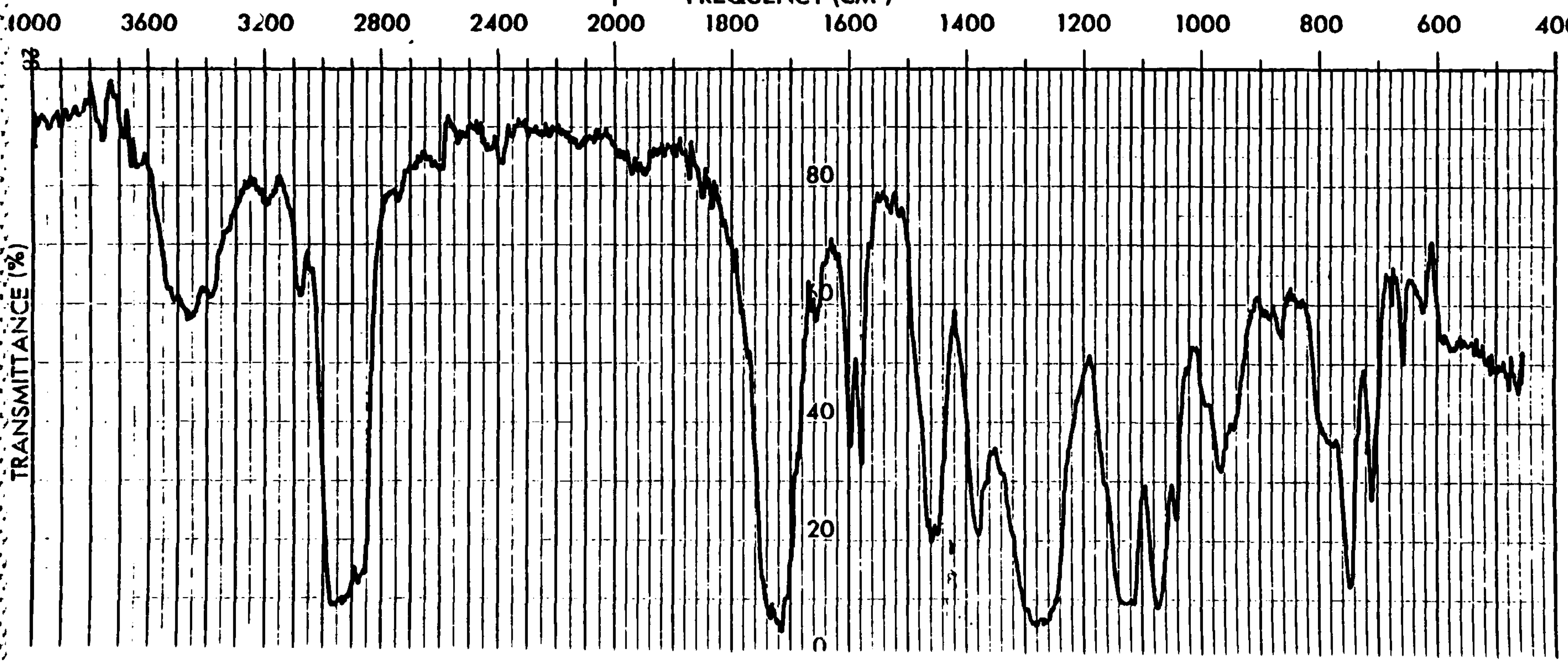
SPEED ___ NORMAL ✓ ___ FAST ___
SLITS ___ NORMAL ✓ ___ WIDE ___
PHASE
CONCENTRATION
THICKNESS
DATE 6/11/83
OPERATOR

PERKIN-ELMER

SPECTRUM NO.
SAMPLE 1 22-H 22 H
KBr Window

SAMPLE 2

SAMPLE B - hexane extract SPECTRUM NO.



NO. 007-1271

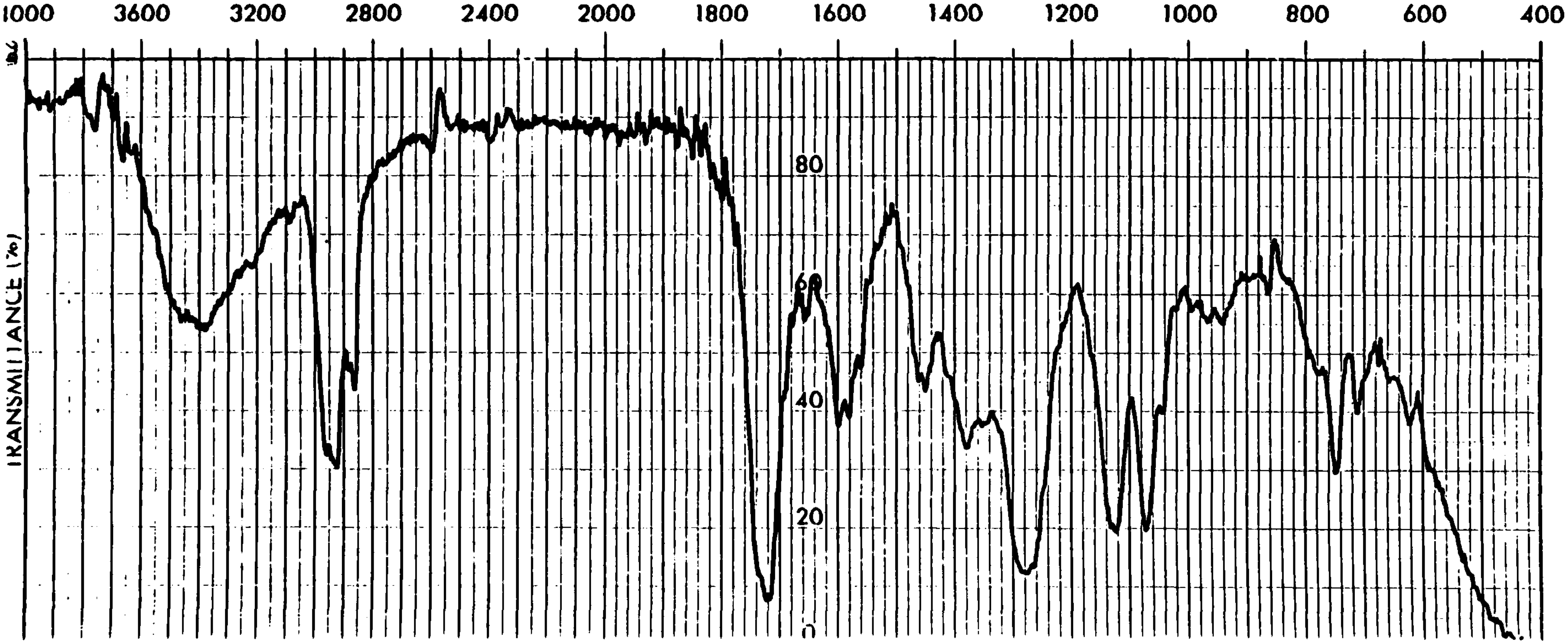
REMARKS
Extract from Ear Plug Sample #22 with Methanol
Oven over 15 min. @ 70 °C

ORIGIN
PURITY
SPEED ____ NORMAL ✓ FAST
SLITS ____ NORMAL ✓ WIDE
PHASE
CONCENTRATION
THICKNESS
DATE 6/14/83
OPERATOR

PERKIN-ELMER

SPECTRUM NO.
SAMPLE 1 22-M
K Br Window
SAMPLE 2

SAMPLE B methanol extract SPECTRUM NO.



NO. 007-1271

REMARKS
Solid sample after extraction of Ear Plug # 23
new mull

ORIGIN
PURITY
SPEED NORMAL ✓ FAST
SLITS NORMAL ✓ WIDE
PHASE
CONCENTRATION
THICKNESS
DATE 6/14/83
OPERATOR

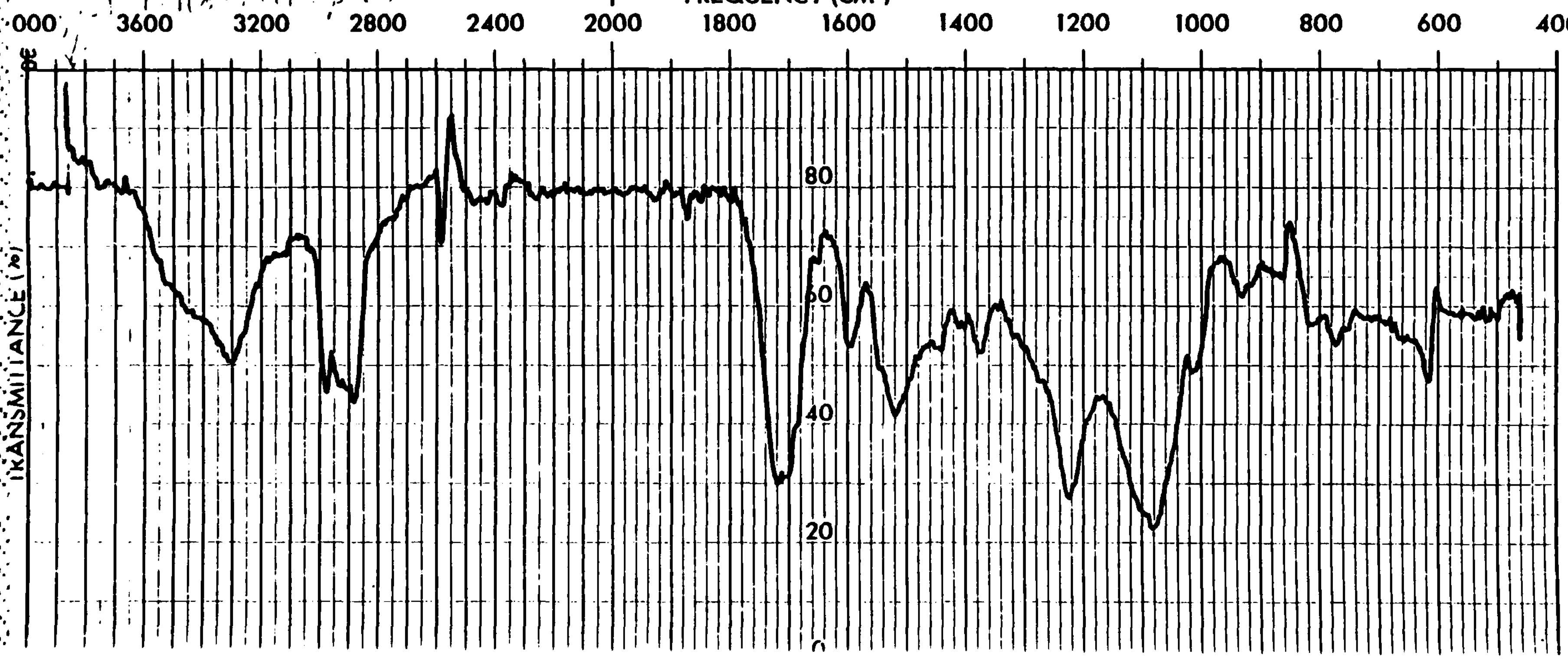
PERKIN-ELMER

SPECTRUM NO.
SAMPLE 1 23
K Br Mull
SAMPLE 2

#5

SAMPLE C extracted foam SPECTRUM NO.

FREQUENCY (CM⁻¹)



NO. 007-1271

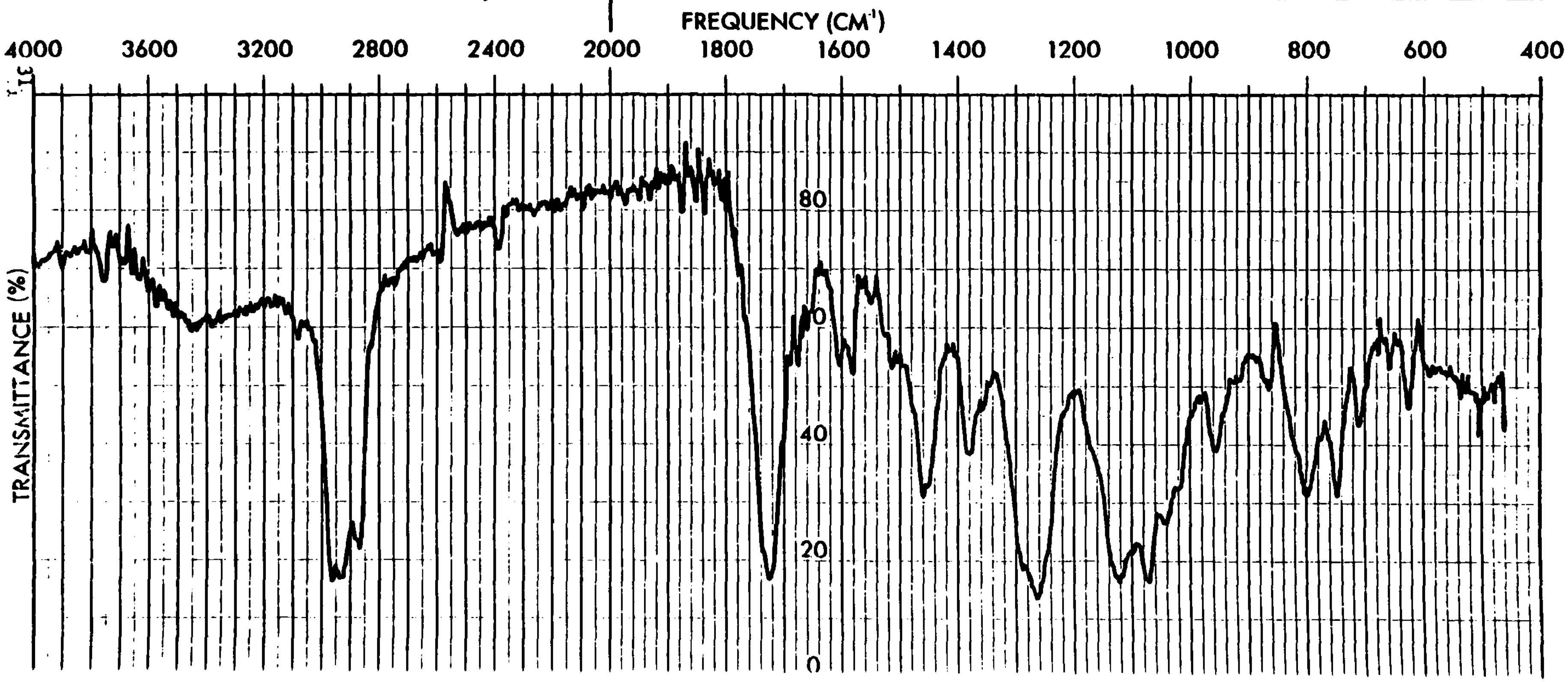
REMARKS
Extract from Ear Plug
Sample #29 with Acetone
In oven over 15 min @
70°C

ORIGIN ____
PURITY ____
SPEED ____ NORMAL ✓ FAST ____
SLITS ____ NORMAL ✓ WIDE ____
PHASE ____
CONCENTRATION ____
THICKNESS ____
DATE 6/14/53
OPERATOR ____

PERKIN-ELMER

SPECTRUM NO. 23 A
SAMPLE 1 23 A
K Br Window
SAMPLE 2 ____

SAMPLE C acetone extract SPECTRUM NO. ____



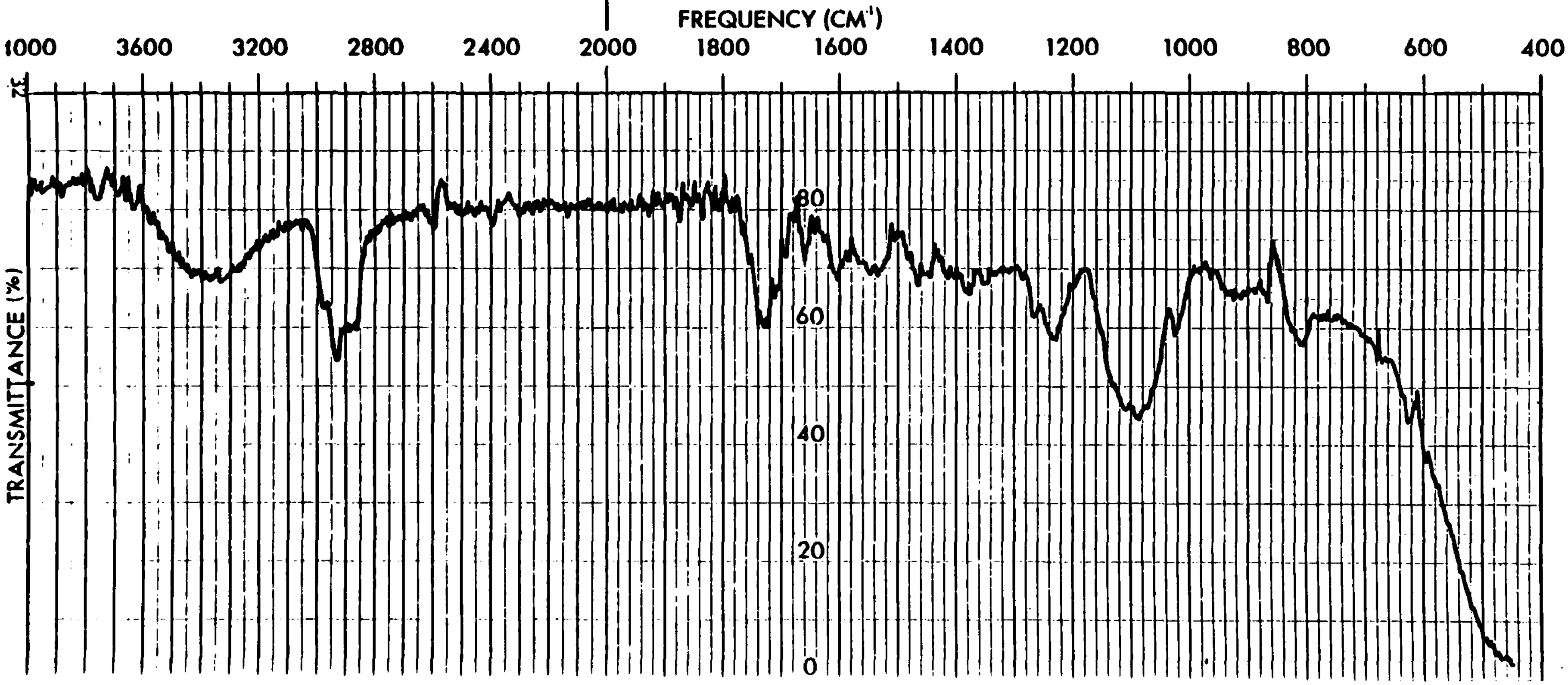
NO. 007-1271

REMARKS
Extract from Ear Plug
Sample # 23 with
Methanol
Oven dried

ORIGIN ____
PURITY ____
SPEED ____ NORMAL ✓ FAST ____
SLITS ____ NORMAL ✓ WIDE ____
PHASE ____
CONCENTRATION ____
THICKNESS ____
DATE 6/10/82
OPERATOR WT

PERKIN-ELMER

SPECTRUM NO. ____
SAMPLE 1 23-M
KBr Window
SAMPLE 2 ____



SAMPLE C - methanol extract SPECTRUM NO. ____

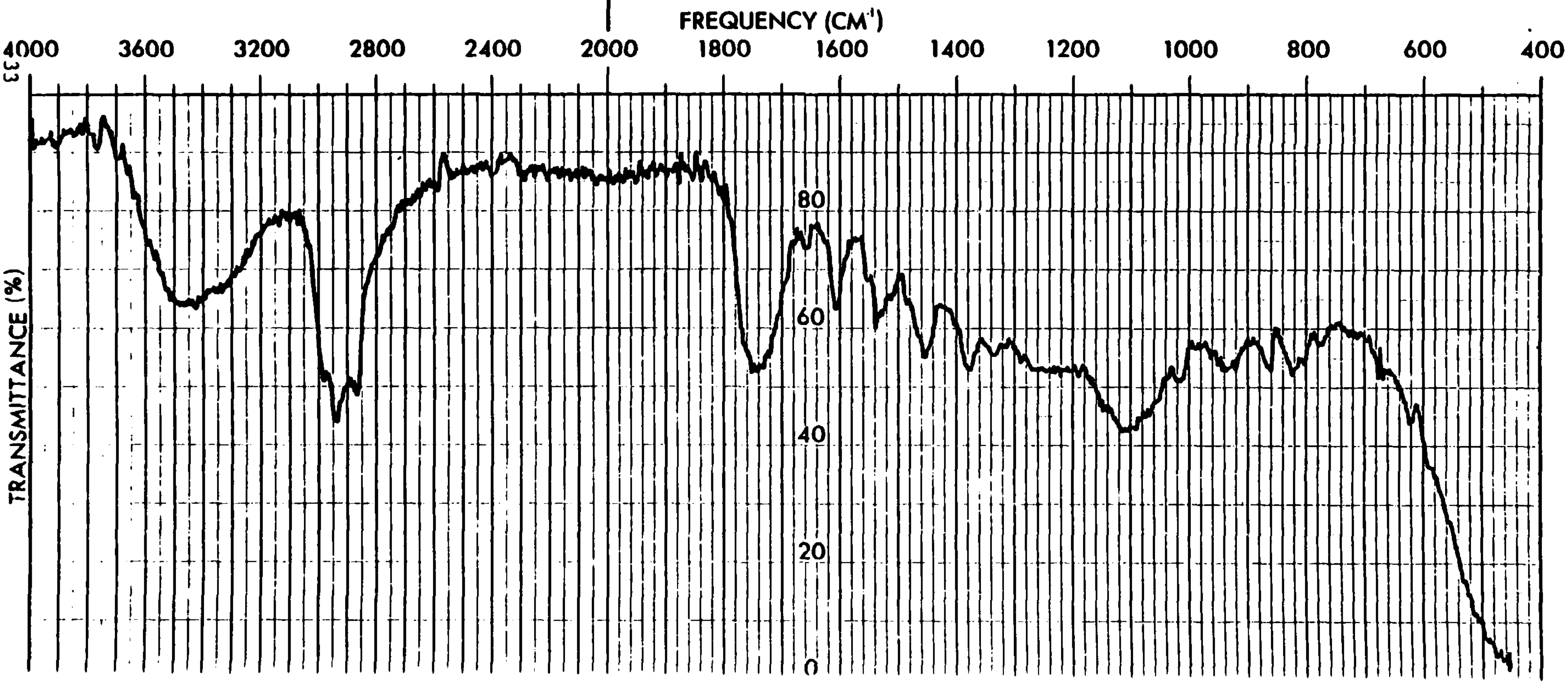
NO. 007-1271

REMARKS
Extract from Ear Plug Sample #23 with Hexane
After 15 min. in oven @ 70°C

ORIGIN
PURITY
SPEED NORMAL ✓ FAST
SLITS NORMAL ✓ WIDE
PHASE
CONCENTRATION
THICKNESS
DATE 6/14/83
OPERATOR

PERKIN-ELMER

SPECTRUM NO. 23
SAMPLE 1 23-H
KBr Window
SAMPLE 2



SAMPLE C - hexane extract SPECTRUM NO.

NO. 007-1271

REMARKS Ear Plug Sample #24

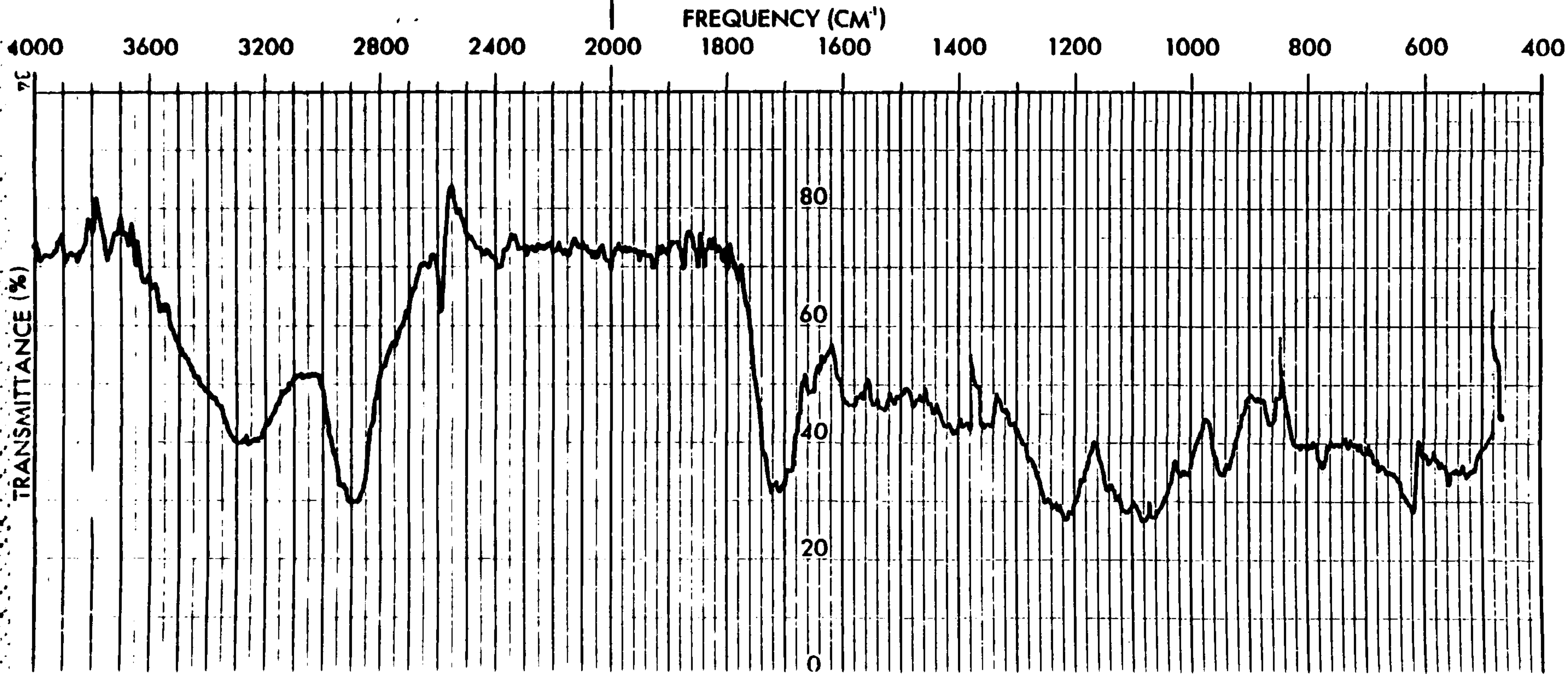
ORIGIN
PURITY

SPEED ___ NORMAL ✓ FAST ___
SLITS ___ NORMAL ✓ WIDE ___
PHASE
CONCENTRATION
THICKNESS
DATE 6/20/83
OPERATOR SD

PERKIN-ELMER

SPECTRUM NO.
SAMPLE 1 24
K Br Mull

SAMPLE 2



SAMPLE D extracted foam SPECTRUM NO.

NO. 007-1271

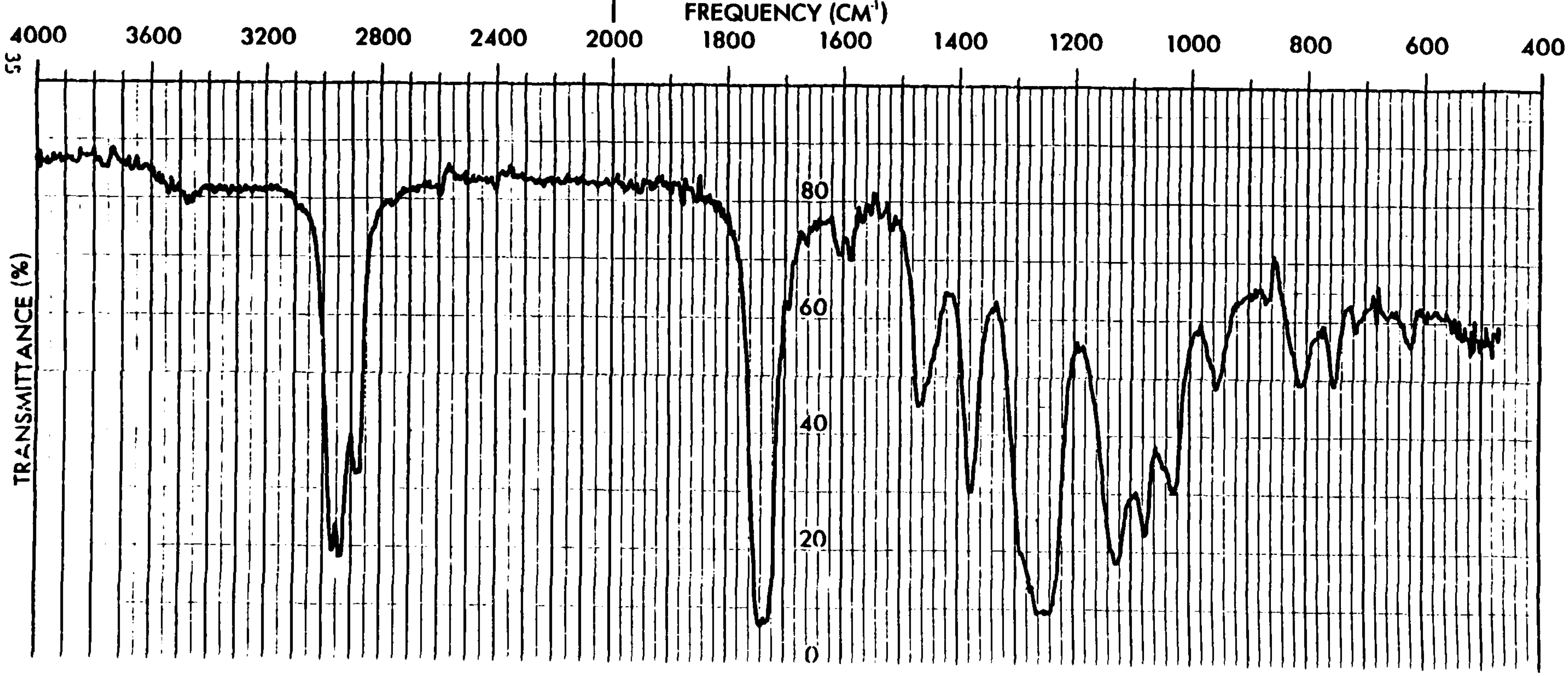
REMARKS
Extract from Ear Plug Sample #24 with Acetone
Oven 15 min. @ 70°C

ORIGIN
PURITY
SPEED NORMAL ✓ FAST
SLITS NORMAL ✓ WIDE
PHASE
CONCENTRATION
THICKNESS
DATE 6/16/83
OPERATOR

PERKIN-ELMER

SPECTRUM NO. 24 A
SAMPLE 1 24 A
K Br Window
SAMPLE 2

SAMPLE D - acetone extract SPECTRUM NO.



NO. 007-1271

REMARKS

Extract from Ear Plug
Sample # 24 with methanol
Oven to dessicator
New film

ORIGIN	
PURITY	
SPEED	NORMAL ✓ FAST
SLITS	NORMAL ✓ WIDE
PHASE	
CONCENTRATION	
THICKNESS	
DATE	6/16/83
OPERATOR	QD

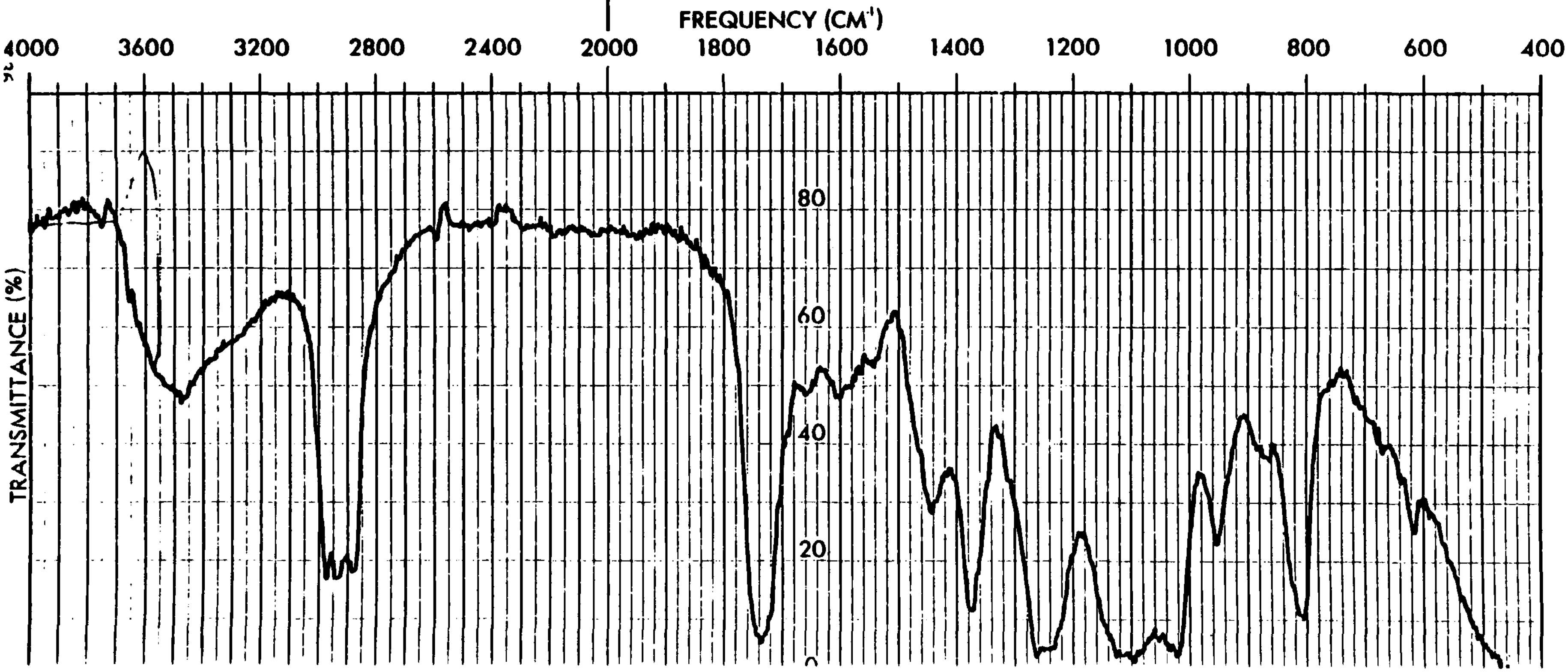
PERKIN-ELMER

SPECTRUM NO.

SAMPLE 1 24-M
K Br Window

SAMPLE 2

SAMPLE D - acetone extract SPECTRUM NO.



NO. 007-1271

REMARKS

Extract from Ear Plug Sample #24 with Hexane

Oven-dried 10min @ 70°C

ORIGIN

PURITY

SPEED NORMAL ✓ FAST

SLITS NORMAL ✓ WIDE

PHASE

CONCENTRATION

THICKNESS

DATE 6/14/83

OPERATOR N(A)

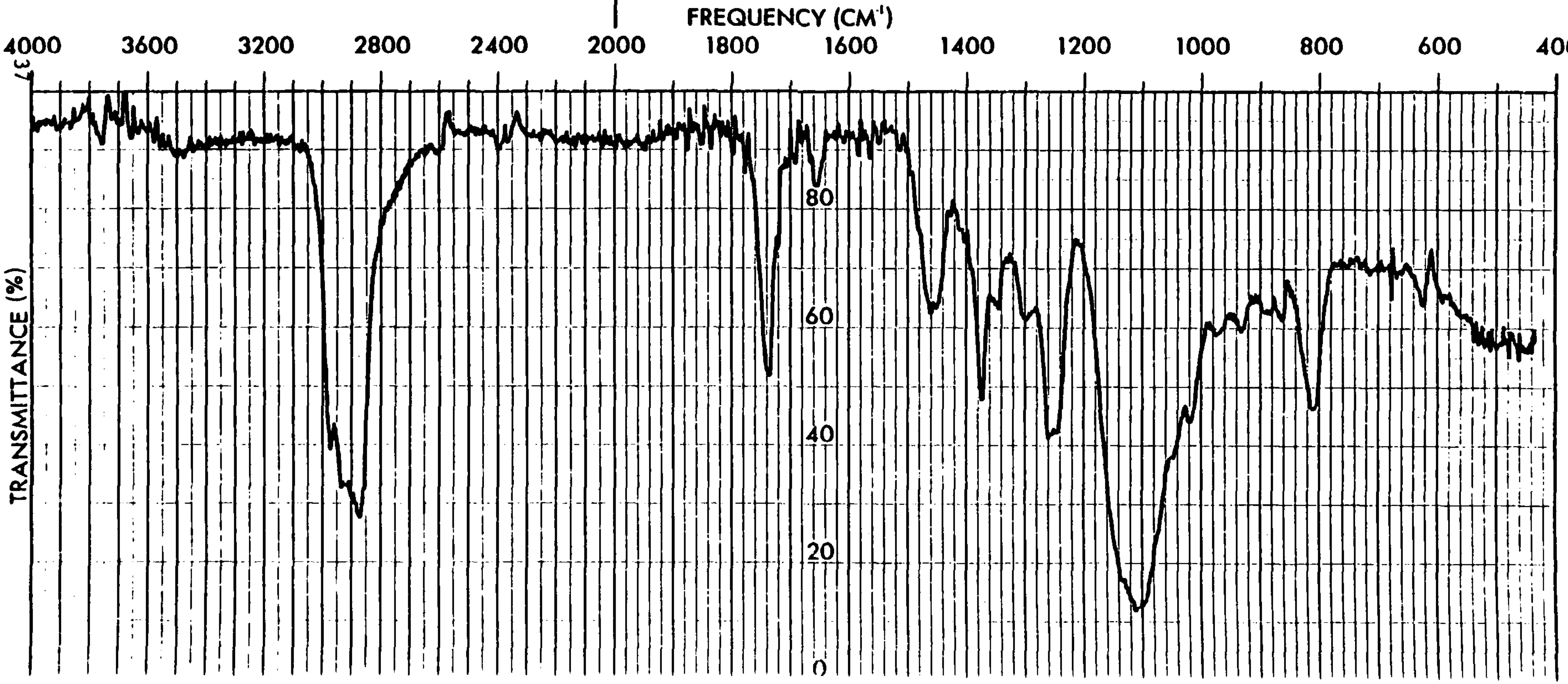
PERKIN-ELMER

SPECTRUM NO. 24 H

SAMPLE 1 24-H

KBr Window

SAMPLE 2



SAMPLE D- hexane extract SPECTRUM NO.

NO. 007-1271

SAMPLE F extracted foam SPECTRUM NO.

REMARKS

Ear Plug Sample # 25
after extractions

ORIGIN

PURITY

SPEED NORMAL ✓ FAST

SLITS NORMAL ✓ WIDE

PHASE

CONCENTRATION

THICKNESS

DATE [illegible]

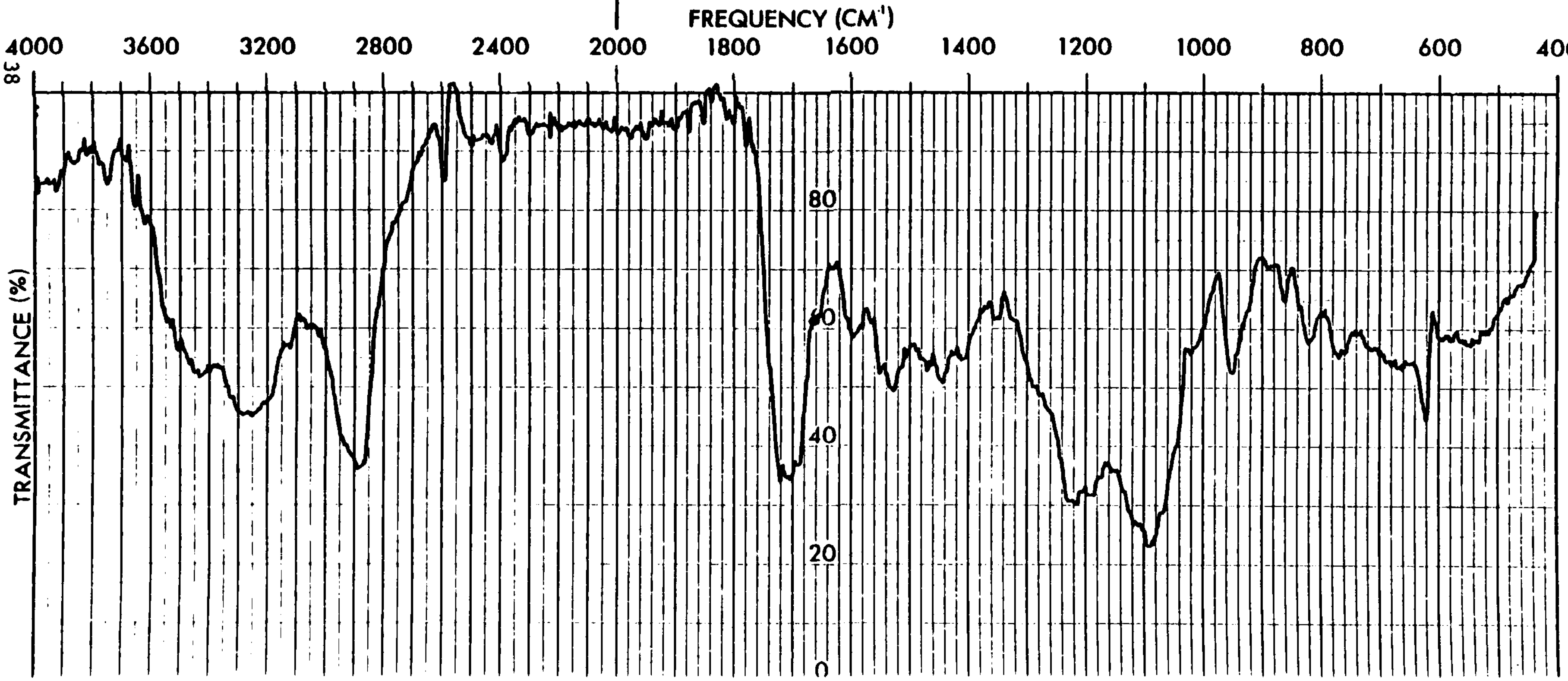
OPERATOR [illegible]

PERKIN-ELMER

SPECTRUM NO.

SAMPLE 1 25 K Br Mull

SAMPLE 2



NO. 007-1271

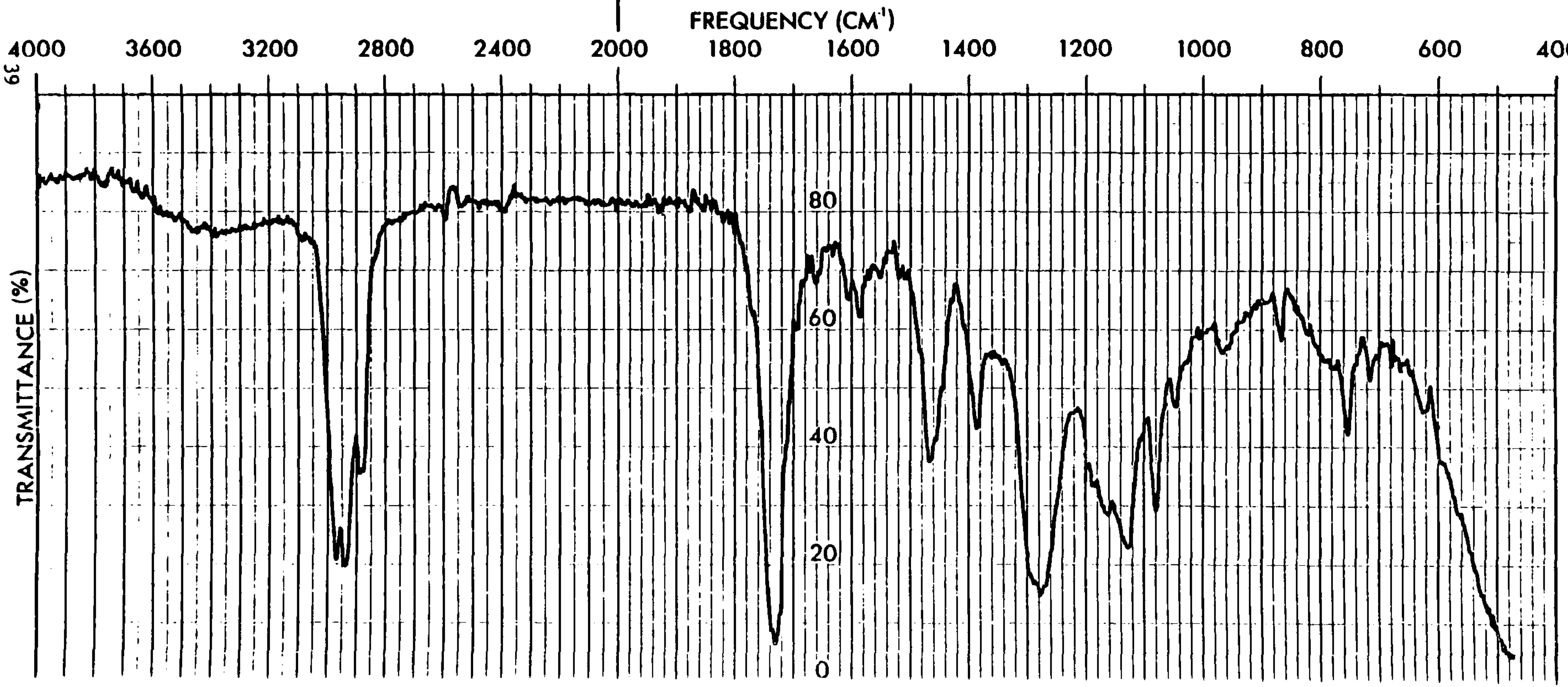
PERKIN-ELMER

REMARKS: Extract from Ear Plug Sample #25 with Acetone
Oven dried @ 70°C

ORIGIN
PURITY
SPEED ___ NORMAL ✓ ___ FAST
SLITS ___ NORMAL ✓ ___ WIDE
PHASE
CONCENTRATION
THICKNESS
DATE 6/16/83
OPERATOR JD

SPECTRUM NO.
SAMPLE 1 25-A 25 A
KBr Window
SAMPLE 2

#



SAMPLE F - acetone extract SPECTRUM NO.

APPENDIX B

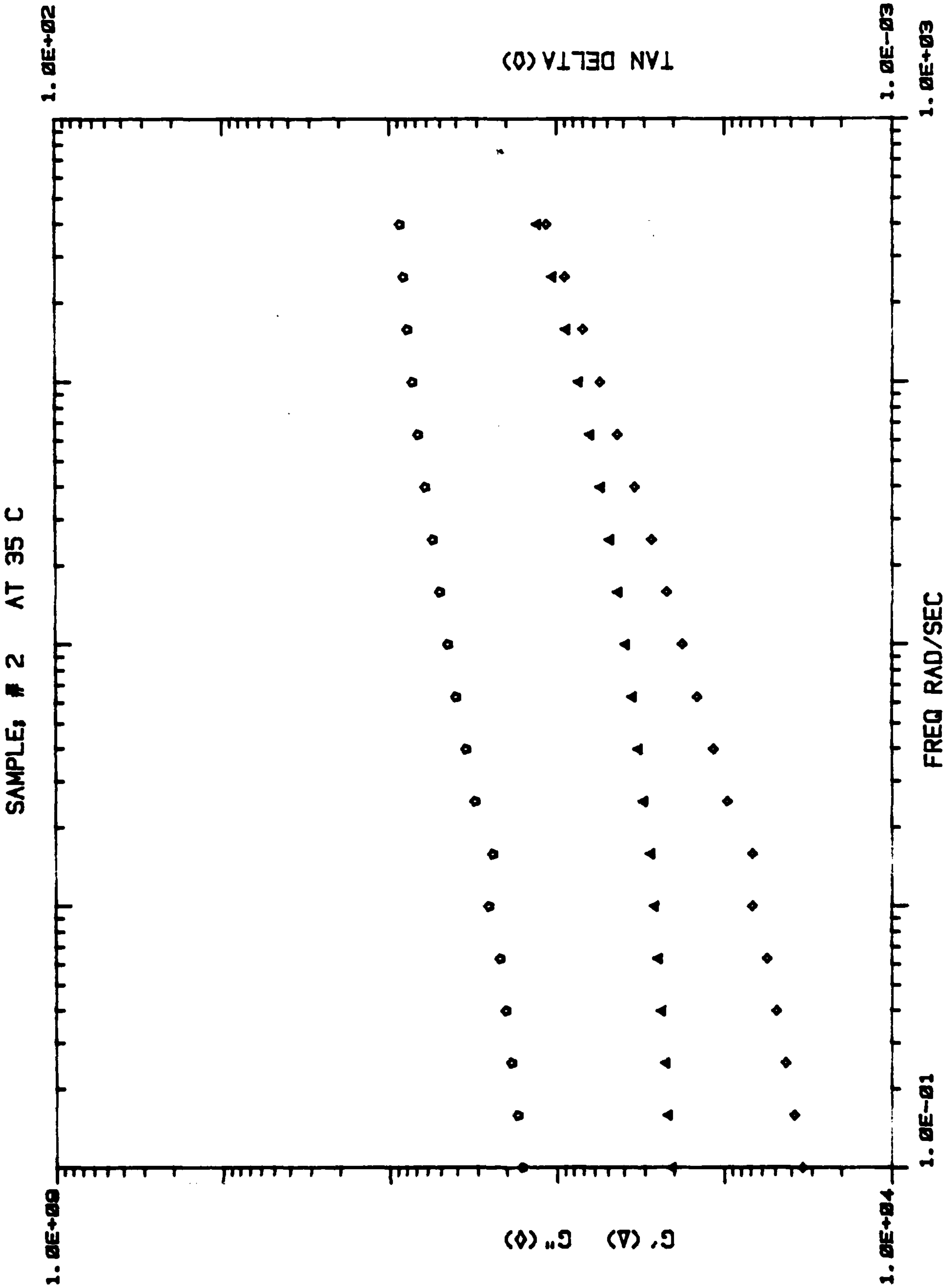
Energy Absorption Measurements Using the Rheometrics Mechanical Spectrometer

DISC & PLATE
GAP [8.265E+00] 8.865
RADIUS [6.700E+00]

SAMPLE: # 2 AT 35 C

RATE SWEEP
STRAIN = 2.000E+00

G' DYNE/SQ CM	G" DYNE/SQ CM	ETA POISE	TANDEL	TEMP DEG.C	RATE RAD/SEC
2.090E+05	3.418E+04	2.118E+06	1.636E-01	35	1.000E-01
2.194E+05	3.803E+04	1.405E+06	1.733E-01	35	1.585E-01
2.278E+05	4.303E+04	9.230E+05	1.889E-01	34	2.512E-01
2.409E+05	4.894E+04	6.174E+05	2.032E-01	35	3.981E-01
2.527E+05	5.585E+04	4.101E=05	2.210E-01	35	6.310E-01
2.652E+05	6.836E+04	2.739E+05	2.577E-01	35	1.000E+00
2.795E+05	6.822E+04	1.815E+05	2.441E-01	35	1.585E+00
3.087E+05	9.648E+04	1.287E+05	3.126E-01	35	2.512E+00
3.306E+05	1.165E+05	8.806E+04	3.523E-01	35	3.981E+00
3.606E+05	1.464E+05	6.168E+04	4.059E-01	35	6.310E+00
3.950E+05	1.787E+05	4.335E+04	4.525E-01	35	1.000E+01
4.379E+05	2.214E+05	3.096E+04	5.055E-01	35	1.585E+01
4.893E+05	2.719E+05	2.228E+04	5.557E-01	35	2.512E+01
5.581E+05	3.448E+05	1.648E+04	6.178E-01	35	3.981E+01
6.419E+05	4.352E+05	1.229E+04	6.780E-01	35	6.310E+01
7.527E+05	5.544E+05	9.348E+03	7.366E-01	35	1.000E+02
8.919E+05	7.008E+05	7.156E+03	7.857E-01	35	1.585E+02
1.083E+06	9.014E+05	5.608E+03	8.326E-01	35	2.512E+02
1.330E+06	1.156E+06	4.427E+03	8.694E-01	35	3.981E+02

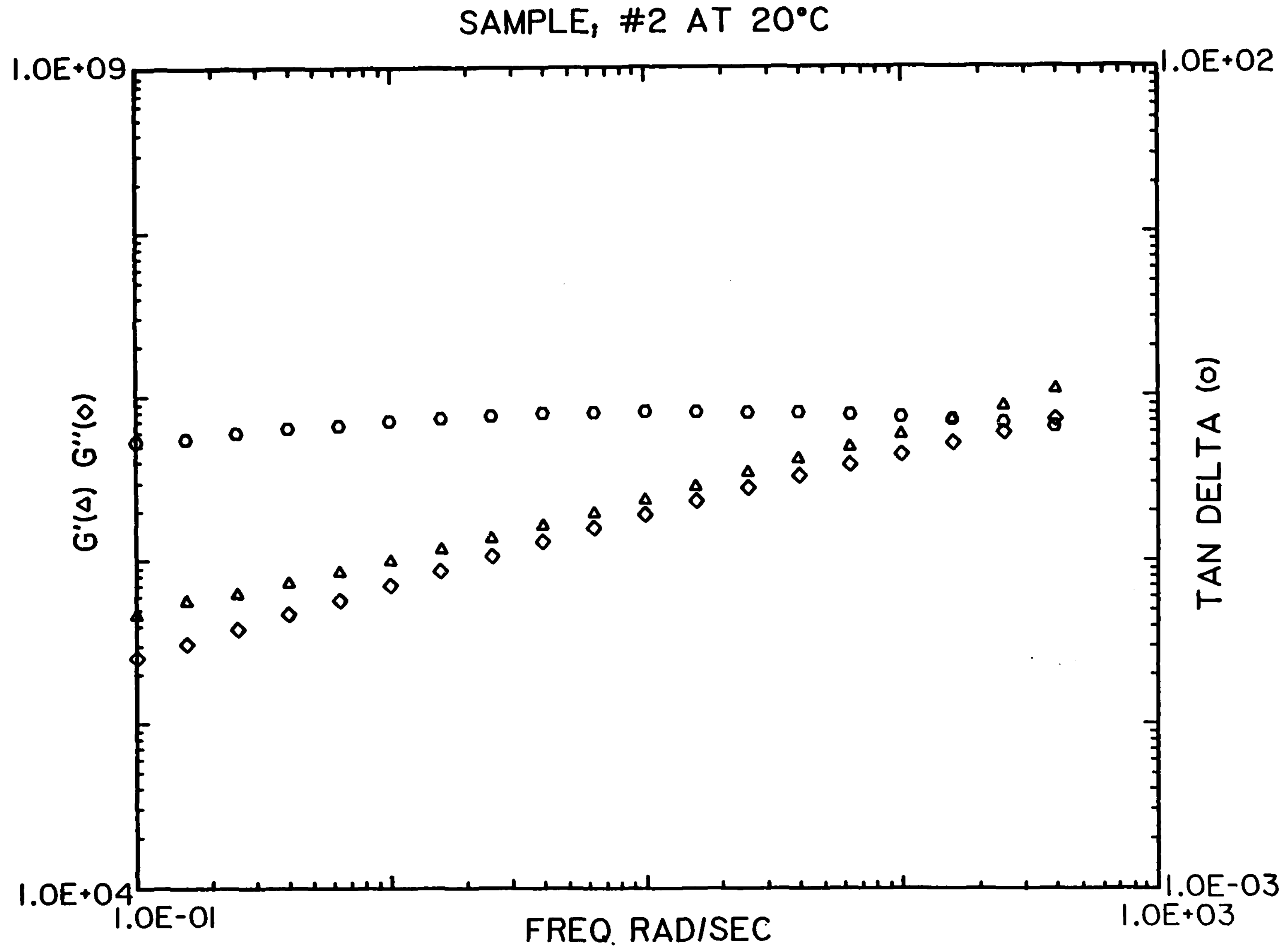


SAMPLE; # 2 AT 35 C
TAN DELTA(◇)
1.0E+02
1.0E-03
1.0E+03
FREQ RAD/SEC
1.0E-01
1.0E+00
1.0E+04
G' (◁) G" (◇)

SAMPLE: # 2 AT 20 C

RATE SWEEP
STRAIN= 2.000E+00

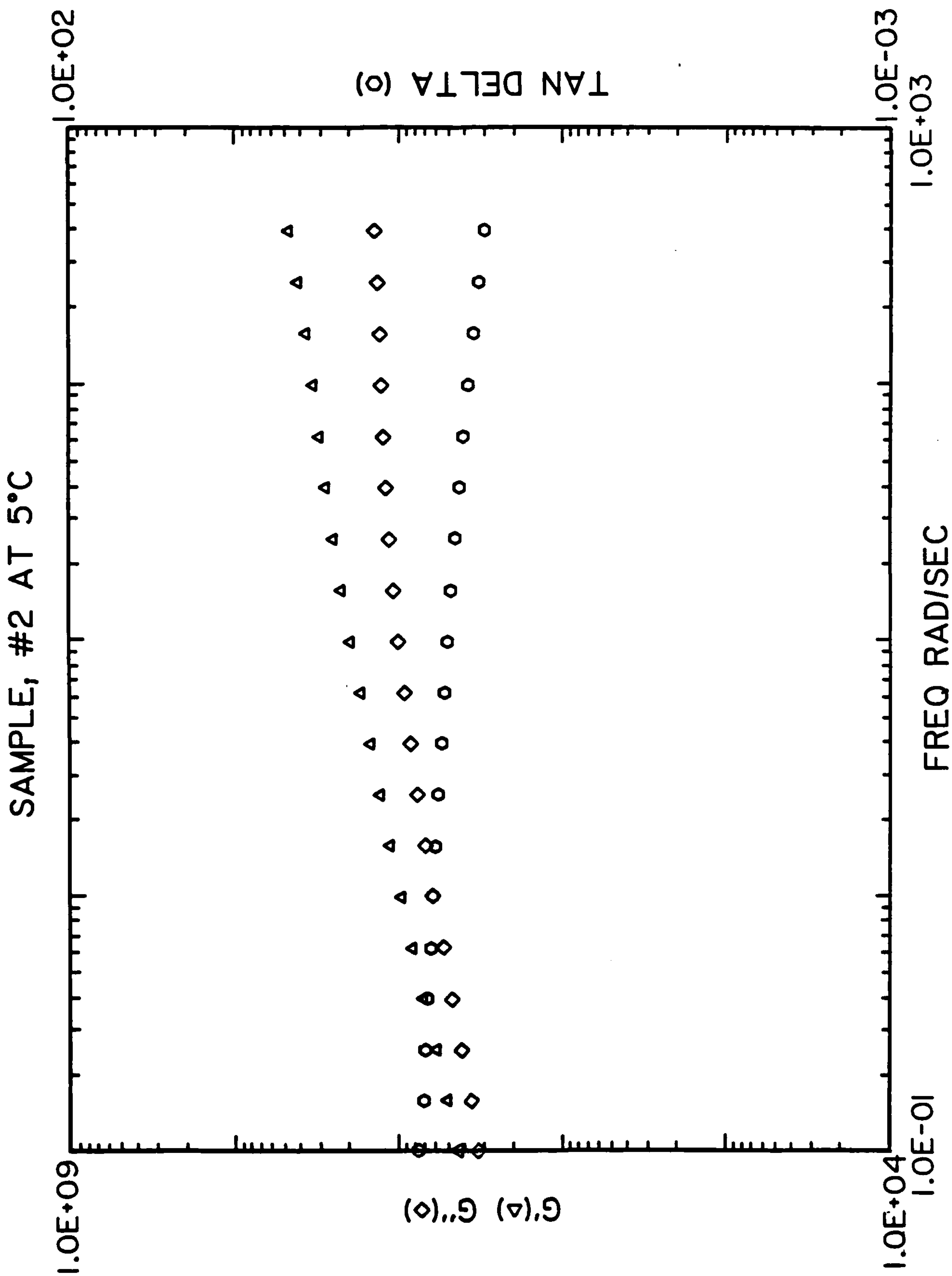
G' DYNE/SQ CM	G'' DYNE/SQ CM	ETA POISE	TANDEL	TEMP DEG.C	RATE RAD/SEC
4.686E+05	2.585E+05	5.352E+06	5.516E-01	19	1.000E-01
5.654E+05	3.109E+05	4.071E+06	5.499E-01	19	1.585E-01
6.351E+05	3.793E+05	2.945E+06	5.973E-01	19	2.512E-01
7.368E+05	4.670E+05	2.191E+06	6.339E-01	19	3.981E-01
8.605E+05	5.685E+05	1.635E+06	6.607E-01	19	6.310E-01
9.992E+05	7.038E+05	1.222E+06	7.044E-01	19	1.000E+00
1.178E+06	8.599E+05	9.200E+05	7.302E-05	19	1.585E+00
1.378E+06	1.049E+06	6.894E+05	7.609E-01	19	2.512E+00
1.652E+06	1.293E+06	5.269E+05	7.829E-01	19	3.981E+00
1.964E+06	1.558E+06	3.973E+05	7.935E-01	19	6.310E+00
2.353E+06	1.877E+06	3.010E+05	7.975E-01	19	1.000E+01
2.838E+06	2.259E+06	2.289E+05	7.961E-01	19	1.585E+01
3.418E+06	2.695E+06	1.733E+05	7.886E-01	19	2.512E+01
4.129E+0	3.206E+06	1.313E+05	7.765E-01	19	3.981E+01
4.876E+06	3.726E+06	9.725E+04	7.641E-01	19	6.310E+01
5.858E+06	4.355E+06	7.300E+04	7.434E-0	19	1.000E+02
7.134E+06	5.085E+06	5.528E+04	7.128E-01	19	1.585E+02
8.637E+06	5.919E+06	4.168E+04	6.853E-01	19	2.512E+02



SAMPLE, #2 AT 20°C
1.0E+09
1.0E+04
G'(△) G''(◇)
1.0E+02
1.0E-03
TAN DELTA (○)
1.0E-01
1.0E+03
FREQ. RAD/SEC

RATE SWEEP
STRAIN= 2.000E+00

G' DYNE/SQ CM	G" DYNE/SQ CM	ETA POISE	TANDEL	TEMP DEG.C	RATE RAD/SEC
4.368E+06	3.242E+06	5.440E+07	7.422E-01	4	1.000E-01
5.156E+06	3.634E+06	3.980E+07	7.049#-01	5	1.585E-01
5.966E+06	4.131E+06	2.889E+07	6.924E-01	4	2.512E-01
7.180E+06	4.739E+06	2.161E+07	6.600E-01	5	3.981E-01
8.395E+06	5.354E+06	1.578E+07	6.378E-01	5	6.310E-01
9.804E+06	6.134E+06	1.157E+07	6.256E-01	5	1.000E+00
1.148E+07	6.865E+06	8.440E+06	5.980E-01	4	1.585E+00
1.326E+07	7.652E+06	6.094E+06	5.772E-01	4	2.512E+00
1.520E+07	8.414E+06	4.364E+06	5.537E-01	4	3.981E+00
1.729E+07	9.154E+06	3.101E+06	5.294E-01	5	6.310E+00
1.981E+07	9.942E+06	2.216E+06	5.019E-01	4	1.000E+01
2.241E+07	1.065E+07	1.565E+06	4.752E-01	4	1.585E+01
2.503E+07	1.127E+07	1.093E+06	4.503E-01	4	2.512E+01
2.800E+07	1.184E+07	7.636E+05	4.228E-01	4	3.981E+01
3.045E+07	1.227E+07	5.203E+05	54.029E-01	4	6.310E+01
3.347E+07	1.264E+07	3.578E+05	3.778E-01	4	1.000E+02
3.695E+07	1.290E+07	2.469E+05	3.492E-01	4	1.585E+02
4.123E+07	1.332E+07	1.725E+05	3.231E-01	4	2.512E+02
4.700E+07	1.391E+07	1.231E+05	2.960E-01	4	3.981E+02


SAMPLE, #2 AT 5°C
TAN DELTA (o)
1.0E+02
1.0E-03
1.0E+03
G'(△) G''(◇)
1.0E+09
1.0E+04
1.0E-01
FREQ RAD/SEC

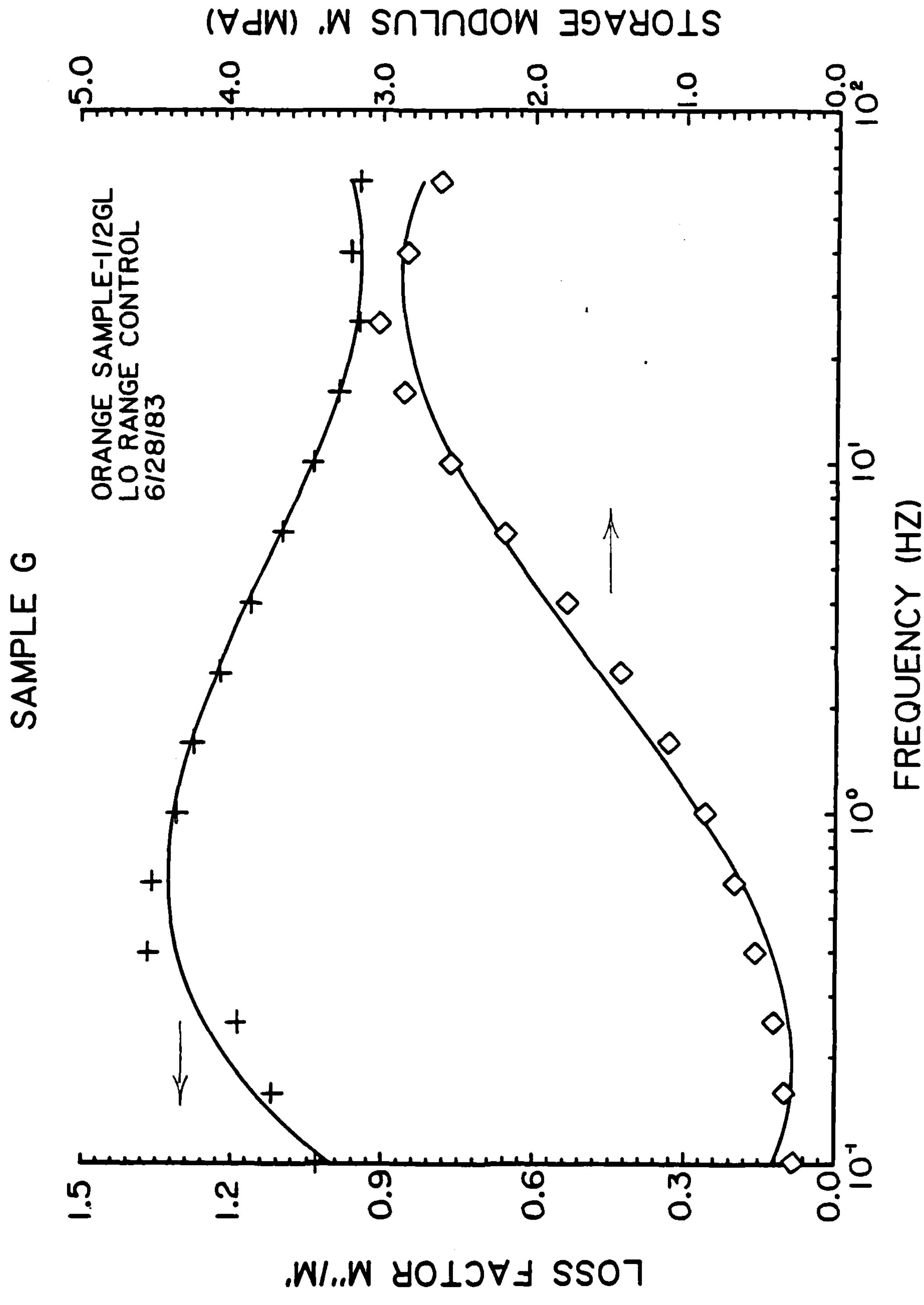
APPENDIX C

Examples of Energy Absorption Data from I-Mass Dynastat

Sample G

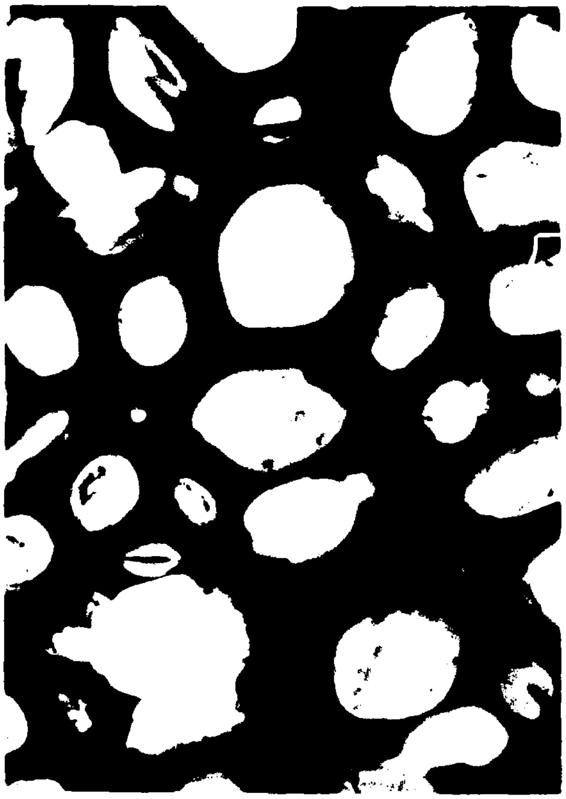
ORANGE SAMPLE
ALGORITHM 3
DYNAMIC MODE
RESULTS IN MPA
X = 0.40000 IN
Y = 0.47000 IN
LOAD SCALE = 1.0000 KG/V
DISP SCALE= 0.050000 MH/V
INERTIAL FO= 450.00 HZ

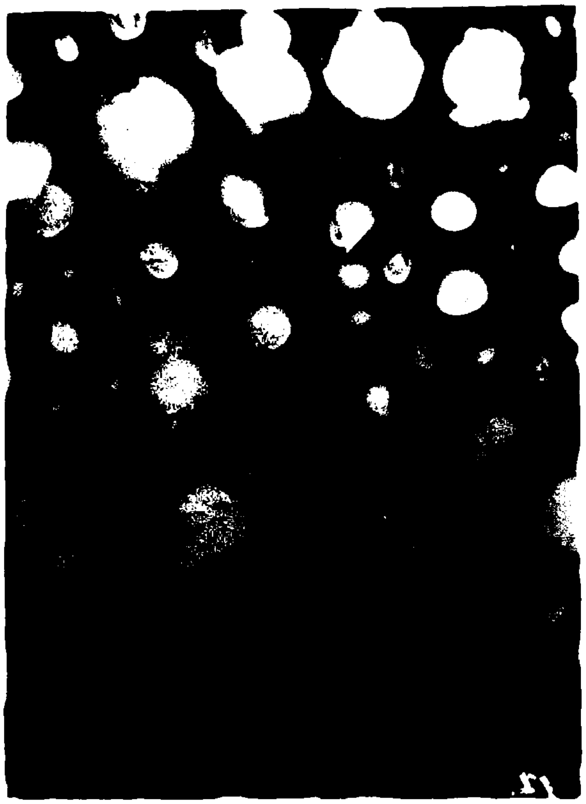
FREQ=	0.100	HZ	FCE=	0.75630	DSP=	35.420	SIG=	0.0066243
			EPS=	0.017431	M =	0.37986	TAN=	1.0296
			M' =	0.26466	M" =	0.27249		
FREQ=	0.158	HZ	FCE=	0.97630	DSP=	35.420	SIG=	0.0085512
			EPS=	0.017431	M =	0.49030	TAN=	1.1164
			M' =	0.32713	M''=	0.36521		
FREQ=	0.251	HZ	FCE=	1.2330	DSP=	35.420	SIG=	0.010800
			EPS=	0.017431	M =	0.61979	TAN=	1.1867
			M' =	0.39939	M''=	0.47396		
FREQ=	0.398	HZ	FCE=	1.7540	DSP=	35.430	SIG=	0.015363
			EPS=	0.017436	M =	0.88095	TAN-	1.3651
			M' =	0.52059	M''=	0.71067		
FREQ=	0.630	HZ	FCE=	2.2370	DSP=	35.440	SIG=	0.19593
			EPS=	0.017441	M =	1.1233	TAN=	1.3577
			M' =	0.66618	M''=	0.90449		
FREQ=	1.000	HZ	FCE=	2.8030	DSP=	35.480	SIG=	0.024551
			EPS=	0.017461	M =	1.4060	TAN=	1.3063
			M' =	0.85465	M''=	1.1165		
FREQ=	1.580	HZ	FCE=	3.5790	DSP=	35.570	SIG=	0.031347
			EPS=	0.017505	M =	1.7907	TAN=	1.2734
			M' =	1.1059	M''=	1.4083		
FREQ=	2.510	HZ	FCE=	4.4980	DSP=	35.700	SIG=	0.039396
			EPS=	0.017569	M =	2.2423	TAN=	1.2187
			M' =	1.4224	M''=	1.7335		
FREQ=	3.980	HZ	FCE=	5.4900	DSP=	35.840	SIG=	0.048082
			EPS=	0.017638	M =	2.7262	TAN=	1.1580
			M' =	1.7818	M''=	2.0633		
FREQ=	6.300	HZ	FCE=	6.5230	DSP=	35.810	SIG=	0.057123
			EPS=	0.017623	M =	3.2409	TAN=	1.0945
			M' =	2.1860	M''=	2.3926		
FREQ=	10.000	HZ	FCE=	7.2950	DSP=	35.290	SIG=	0.063864
			EPS=	0.017367	M =	3.6761	TAN=	1.0348
			M' =	2.5545	M''=	2.6435		
FREQ=	15.840	HZ	FCE=	7.7120	DSP=	34.160	SIG=	0.067464
			EPS=	0.016811	M =	4.0123	TAN=	0.98631
			M' =	2.8566	M''=	2.8175		
FREQ=	25.110	HZ	FCE=	7.8180	DSP=	33.210	SIG=	0.068263
			EPS=	0.016344	M =	4.1756	TAN=	0.94675
			M' =	3.0322	M''=	2.8707		
FREQ=	39.810	HZ	FCE=	7.5050	DSP=	33.660	SIG=	0.065221
			EPS=	0.016565	M =	3.9365	TAN=	0.96264
			M' =	2.8360	M''=	2.7300		
FREQ=	63.090	HZ	FCE=	7.5450	DSP=	36.440	SIG=	0.064786
			EPS=	0.017933	M =	3.6114	TAN=	0.94677
			M' =	2.6224	M''=	2.4829		
FREQ=	100.000	HZ	FCE=	6.1360	DSP=	49.420	SIG=	0.051090
			EPS=	0.024321	M =	2.1004	TAN-	1.4158
			M' =	1.2117	M''=	1.7156		


SAMPLE G
ORANGE SAMPLE-1/2GL
LO RANGE CONTROL
6/28/83
STORAGE MODULUS M' (MPA)
5.0
4.0
3.0
2.0
1.0
0.0
LOSS FACTOR M''/M'
1.5
1.2
0.9
0.6
0.3
0.0
10^{-1}
10^{0}
10^{1}
10^{2}
FREQUENCY (HZ)

APPENDIX D

Representative Photomicrographs of Earplug Sections





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